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(54) **DELTA CONNECTED RESONANT TURN OFF CIRCUITS**

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(51) **Int. Cl.**

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G06F 1/26	(2006.01)
G06F 1/28	(2006.01)
H03K 17/72	(2006.01)
H03K 17/13	(2006.01)
H03K 17/04	(2006.01)
H02J 3/00	(2006.01)

(52) **U.S. Cl.**
CPC ***H02J 9/06*** (2013.01); ***G06F 1/263*** (2013.01); ***G06F 1/28*** (2013.01); ***H02J 3/007*** (2020.01); ***H02J 3/0073*** (2020.01); ***H02J 9/068*** (2020.01); ***H03K 17/0403*** (2013.01); ***H03K 17/136*** (2013.01); ***H03K 17/72*** (2013.01)

(58) **Field of Classification Search**
CPC H02J 3/007; H02J 3/005; H02J 3/0073; H02J 9/062; H02J 9/068; H03K 17/56; H03K 17/0403; H03K 17/72; H03K 17/136
See application file for complete search history.

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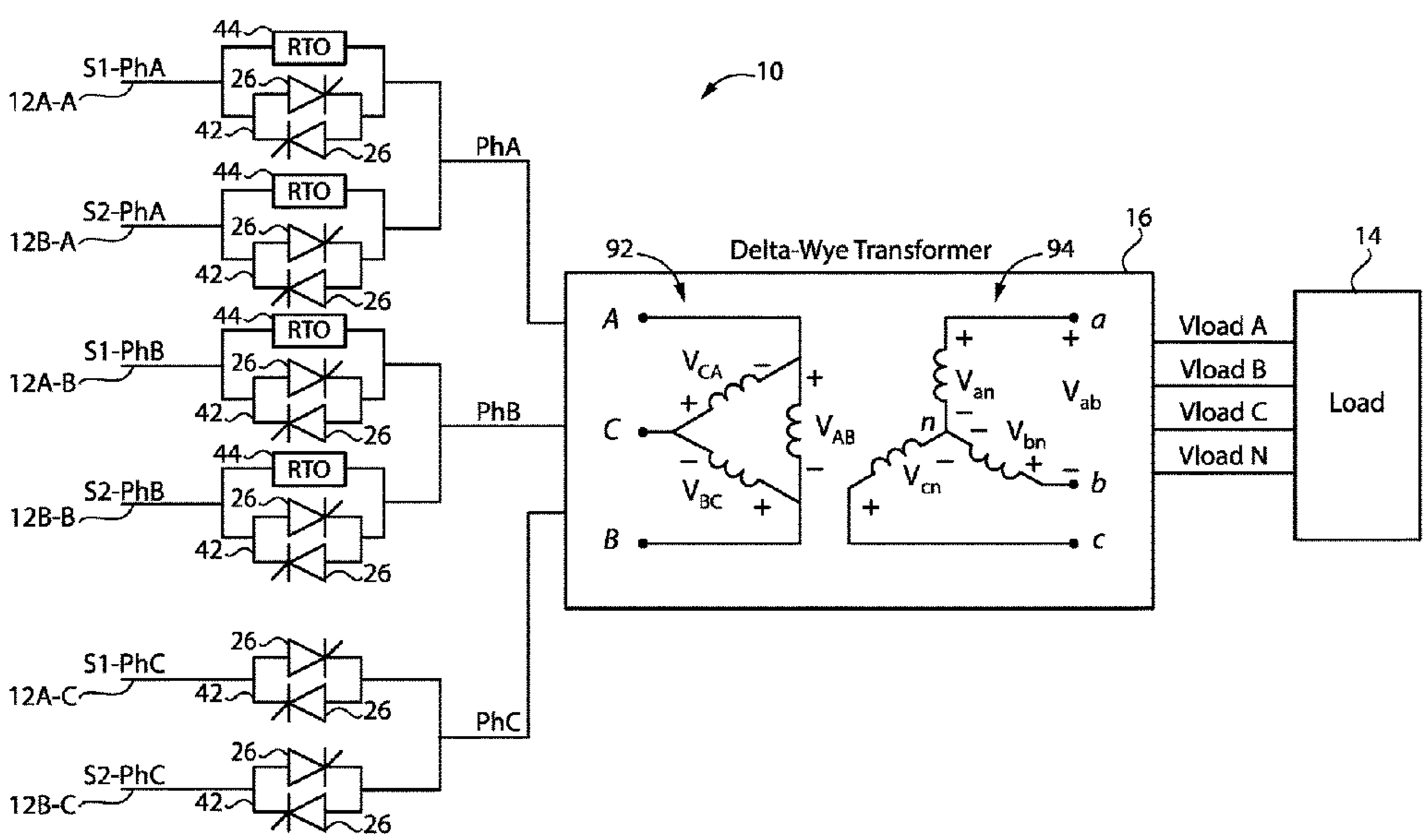
(57) **ABSTRACT**

A static transfer switch is provided for supplying power to a load alternately from two different power sources. Switching between the two power sources may occur within a fraction of one electrical cycle. In response to sensing degraded performance in the power source supplying the load, resonant turn off circuits connected directly to the main switches of two phases of the power source are actuated to commutate the respective main switches. The main switch of the third phase is commutated with one or more of the resonant turn off circuits through the delta side of a transformer connected to the three phases of the power source.

21 Claims, 14 Drawing Sheets



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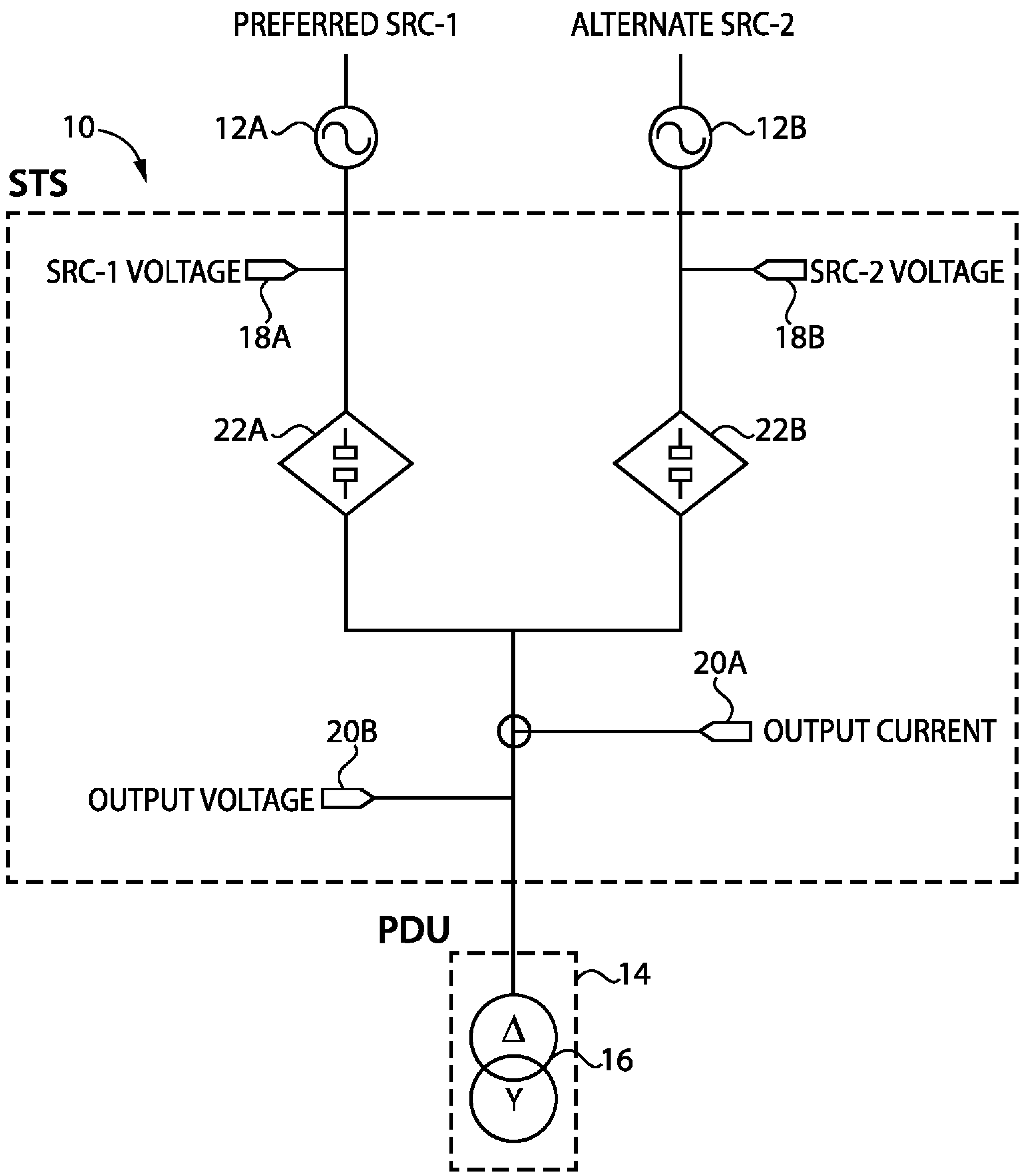


PRIOR ART

FIG. 1

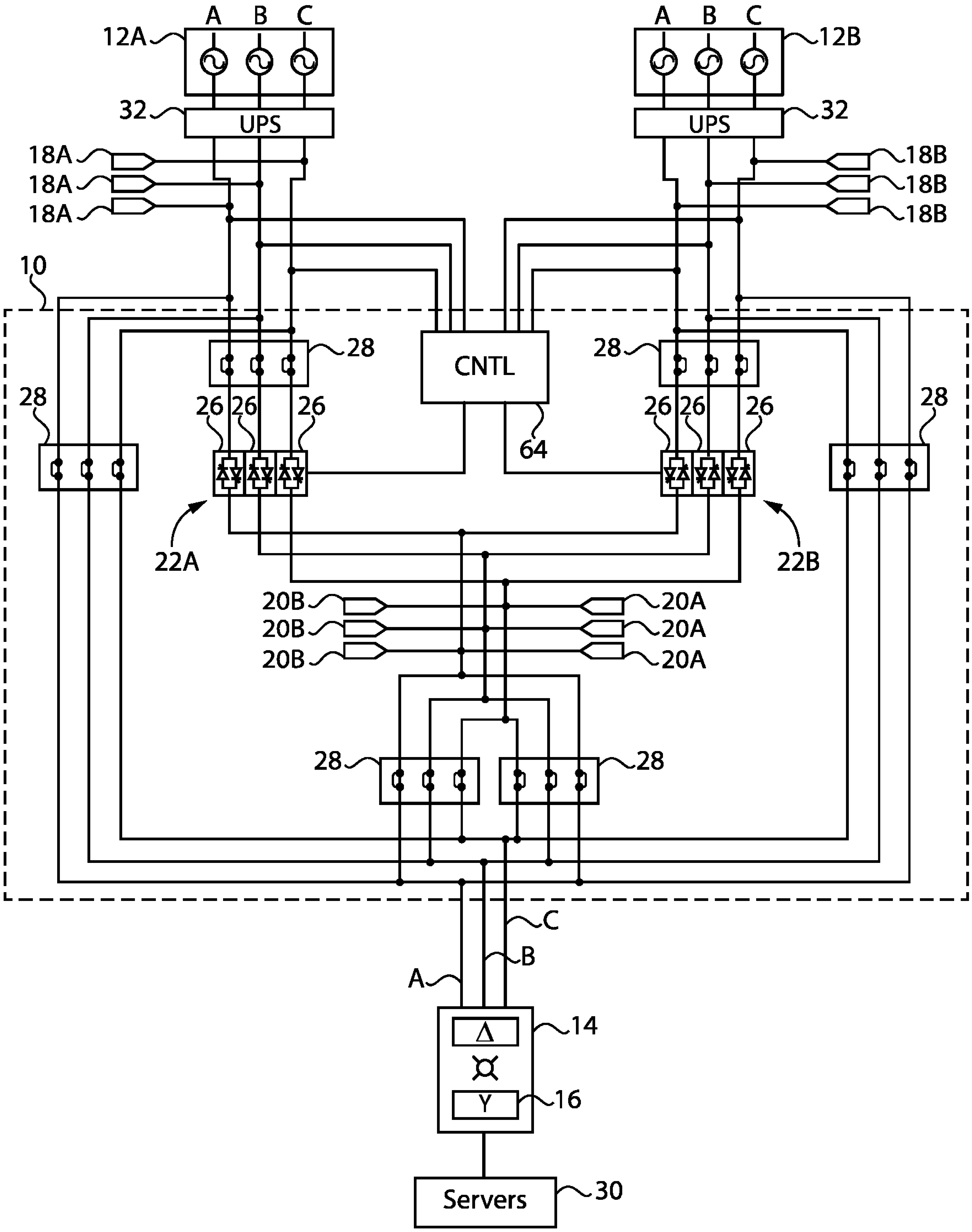
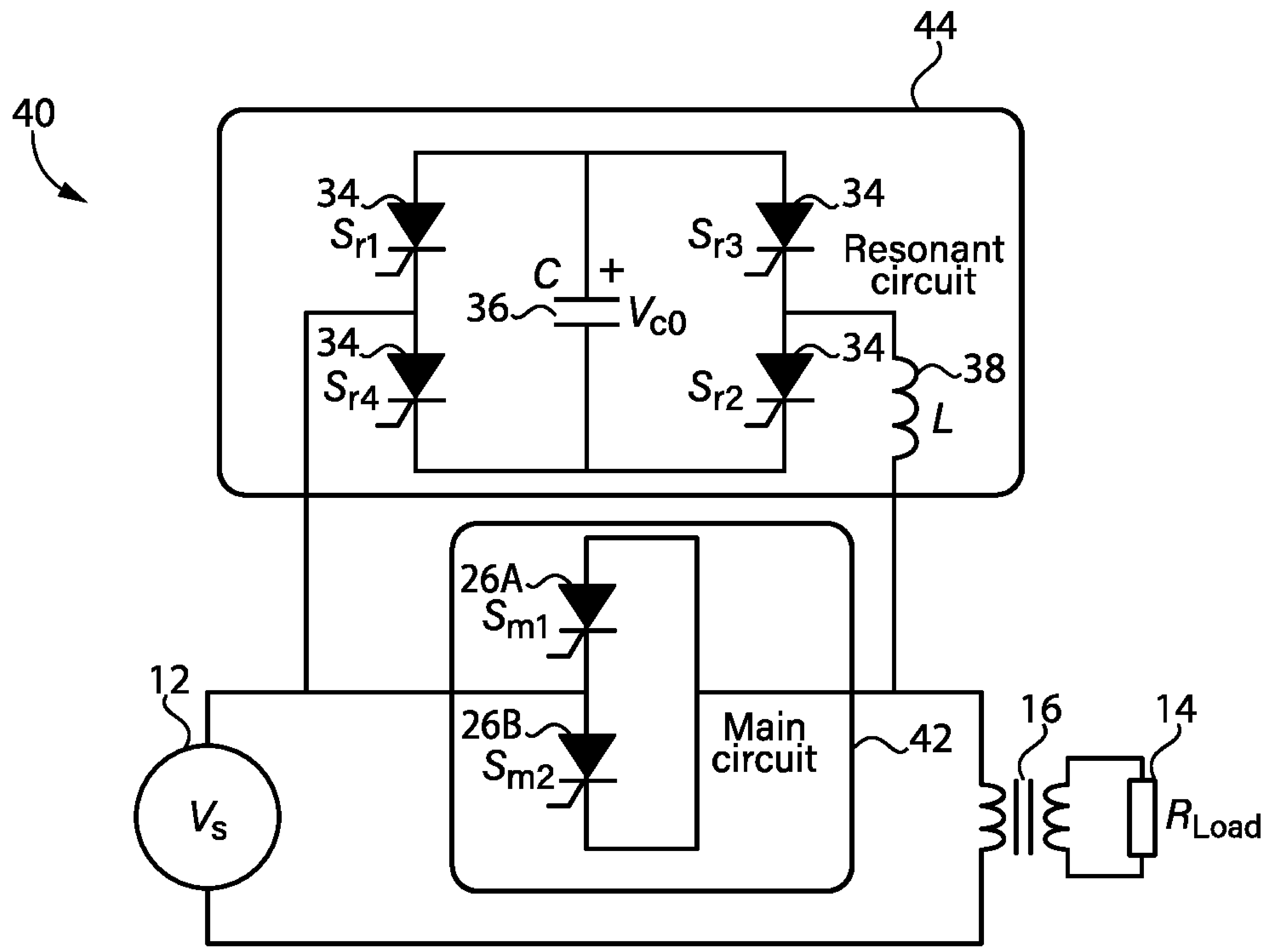
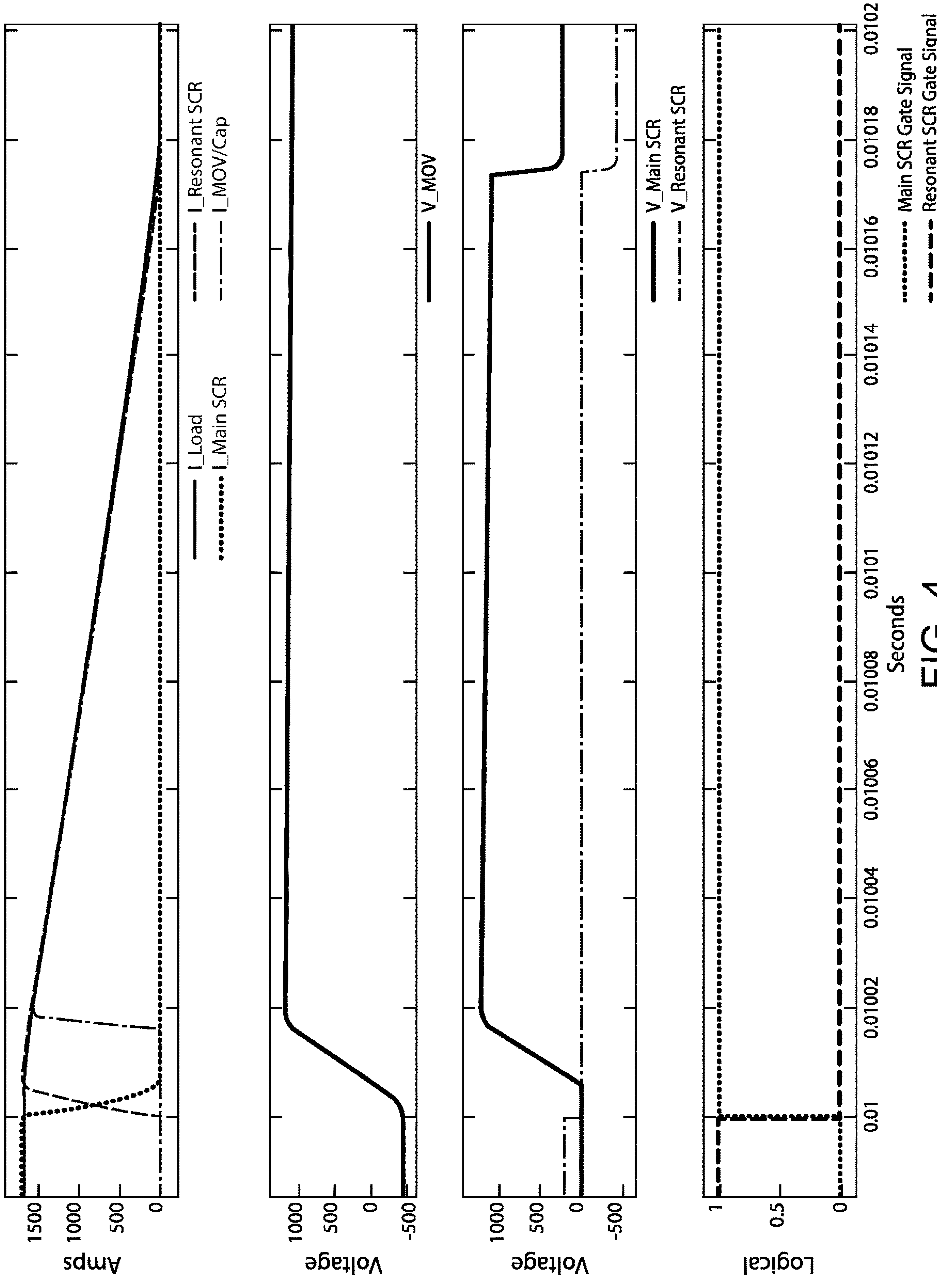

A
B
C
12A
12B
32
UPS
UPS
32
18A
18A
18A
18B
18B
18B
10
28
CNTL
28
28
26
26
26
64
26
26
26
28
22A
22B
20B
20B
20B
20A
20A
20A
28
28
C
B
A
14
Δ
Y
16
Servers
30

FIG. 2



44
40
34
S_{r1}
34
S_{r3}
Resonant circuit
C
+
36
V_{c0}
34
S_{r4}
34
S_{r2}
38
L
26A
S_{m1}
12
26B
S_{m2}
Main circuit
42
16
14
V_s
R_{Load}

FIG. 3



Amps
1500
1000
500
0
I_Load
I_Main SCR
I_Resonant SCR
I_MOV/Cap
Voltage
1000
500
0
-500
V_MOV
Voltage
1000
500
0
-500
V_Main SCR
V_Resonant SCR
Logical
1
0.5
0
Main SCR Gate Signal
Resonant SCR Gate Signal
0.01
0.01002
0.01004
0.01006
0.01008
0.0101
0.01012
0.01014
0.01016
0.01018
0.0102
Seconds

FIG. 4

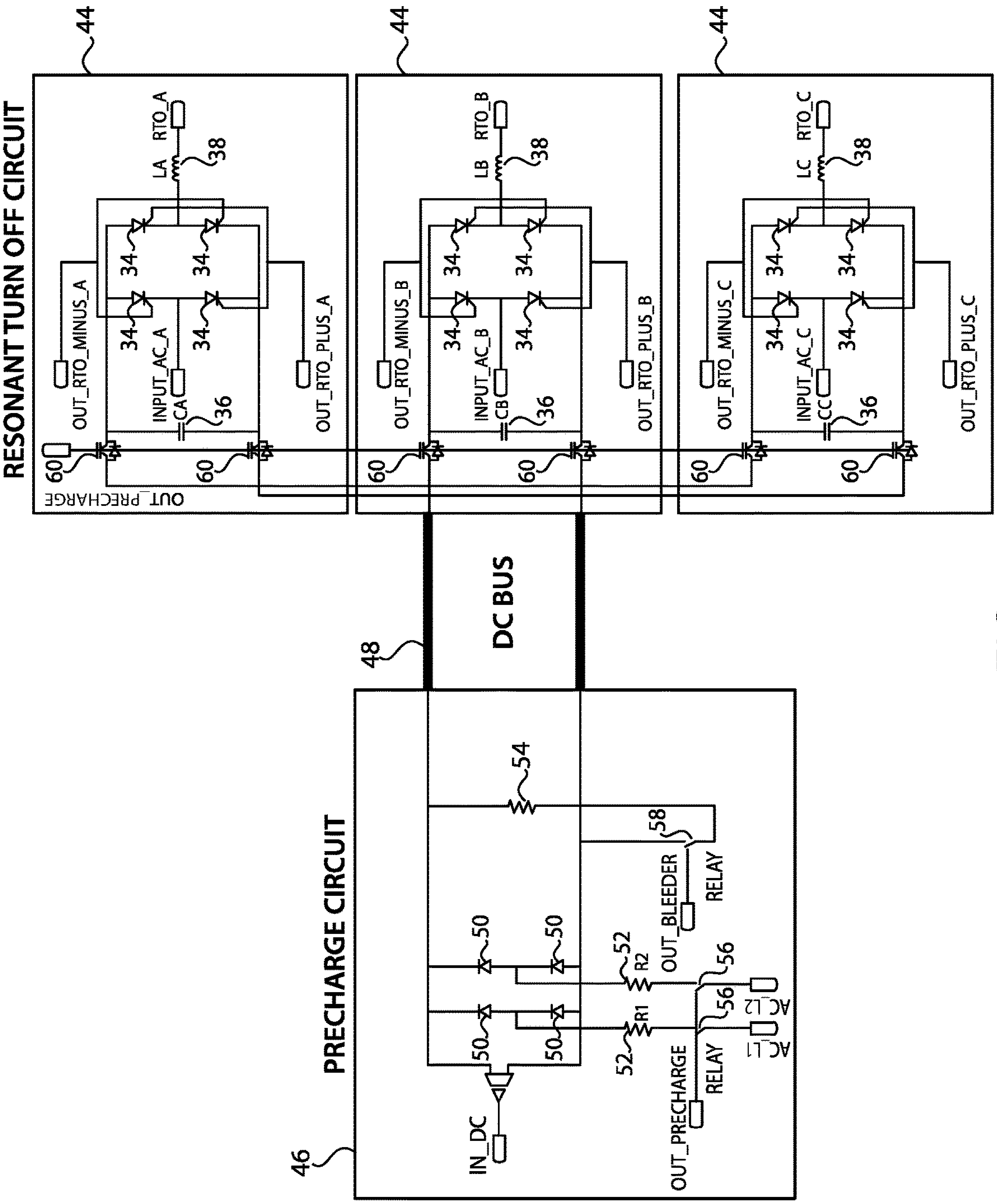

RESONANT TURN OFF CIRCUIT
44
44
44
RTO_A
LA
38
RTO_B
LB
38
RTO_C
LC
38
34
OUT_RTO_MINUS_A
INPUT_AC_A
OUT_RTO_PLUS_A
CA
36
OUT_RTO_MINUS_B
INPUT_AC_B
OUT_RTO_PLUS_B
CB
36
OUT_RTO_MINUS_C
INPUT_AC_C
OUT_RTO_PLUS_C
CC
36
60
OUT_PRECHARGE
DC BUS
48
PRECHARGE CIRCUIT
54
58
OUT_BLEEDER
RELAY
50
52
R2
R1
56
AC_L2
AC_L1
OUT_PRECHARGE
RELAY
IN_DC
46

FIG. 5

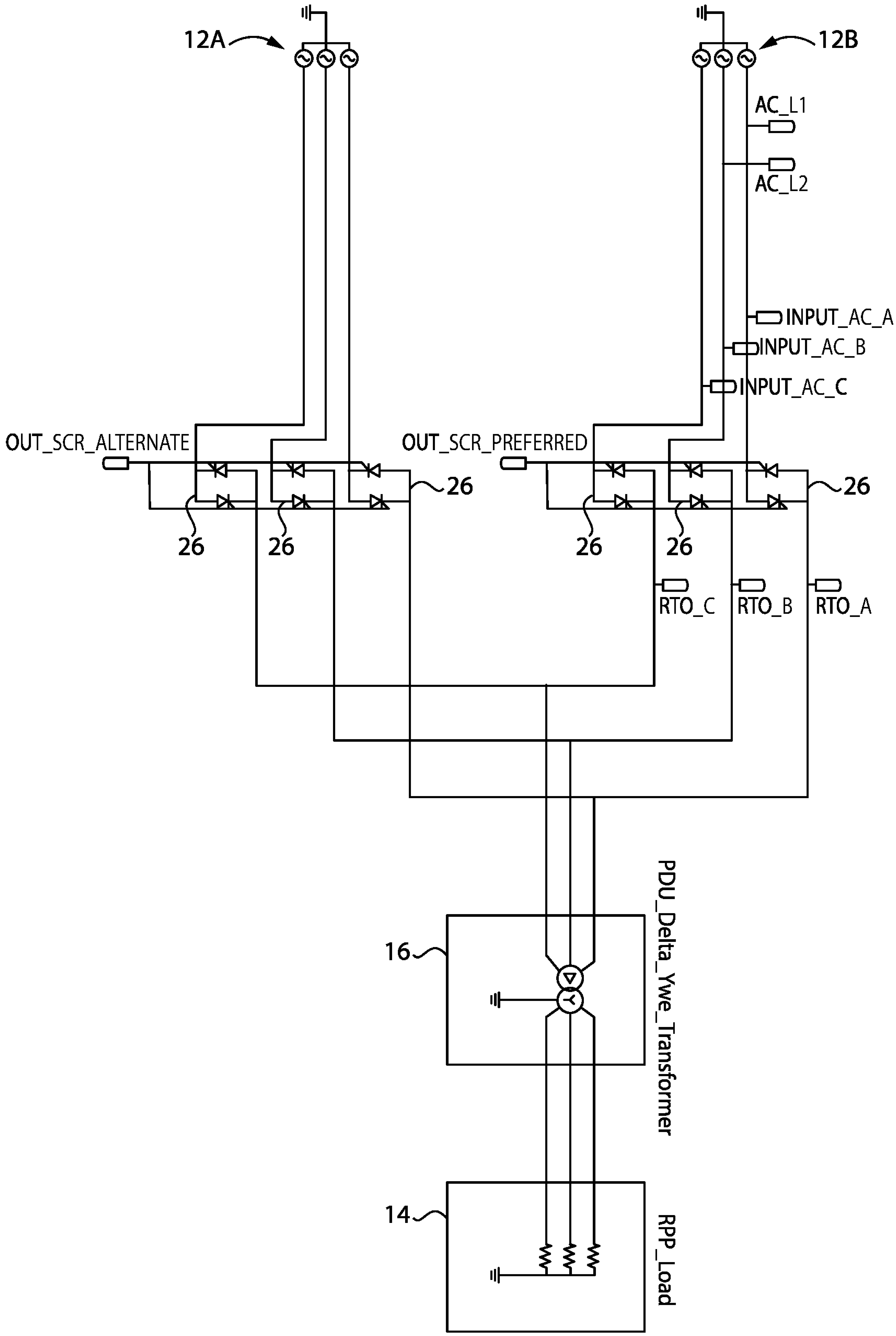

12A
12B
AC_L1
AC_L2
INPUT_AC_A
INPUT_AC_B
INPUT_AC_C
OUT_SCR_ALTERNATE
OUT_SCR_PREFERRED
26
26
26
26
26
26
RTO_C
RTO_B
RTO_A
16
PDU_Delta_Ywe_Transformer
14
RPP_Load

FIG. 6

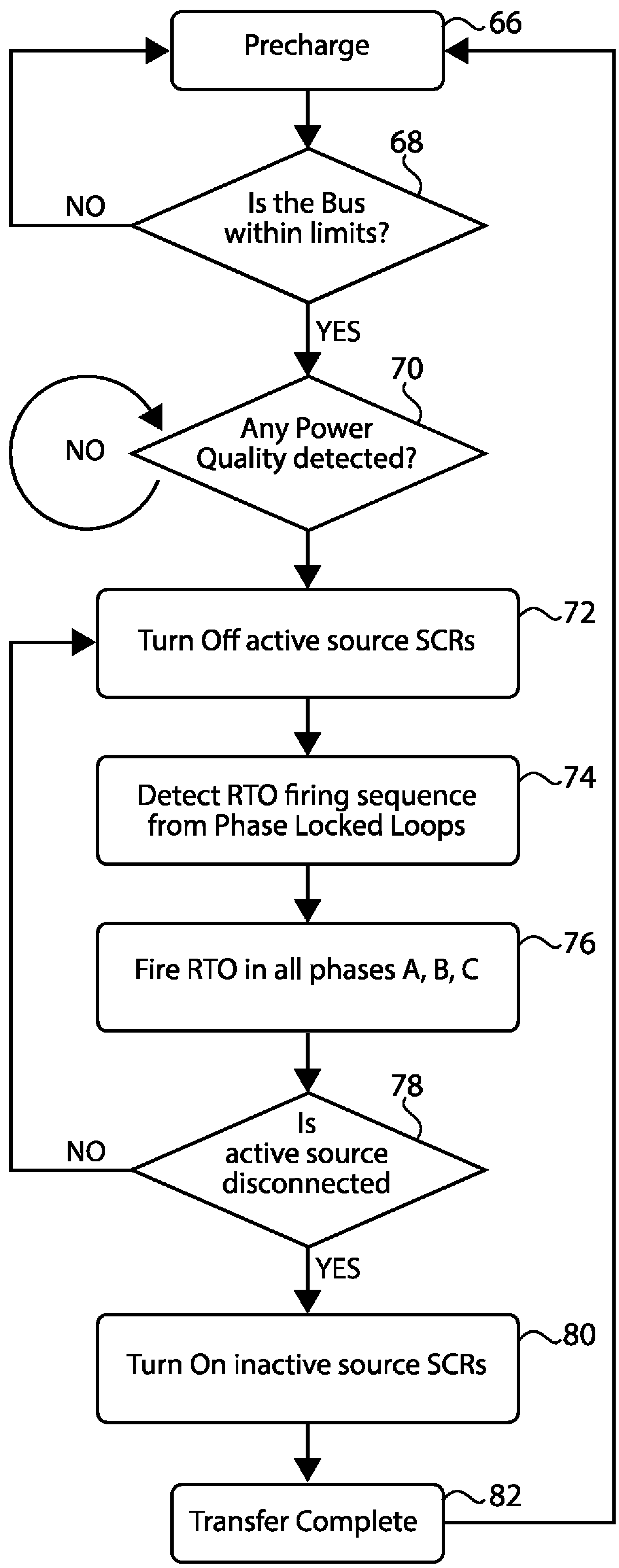

Precharge
66
68
Is the Bus within limits?
NO
YES
70
Any Power Quality detected?
NO
Turn Off active source SCRs
72
Detect RTO firing sequence from Phase Locked Loops
74
Fire RTO in all phases A, B, C
76
78
Is active source disconnected
NO
YES
Turn On inactive source SCRs
80
Transfer Complete
82

FIG. 7

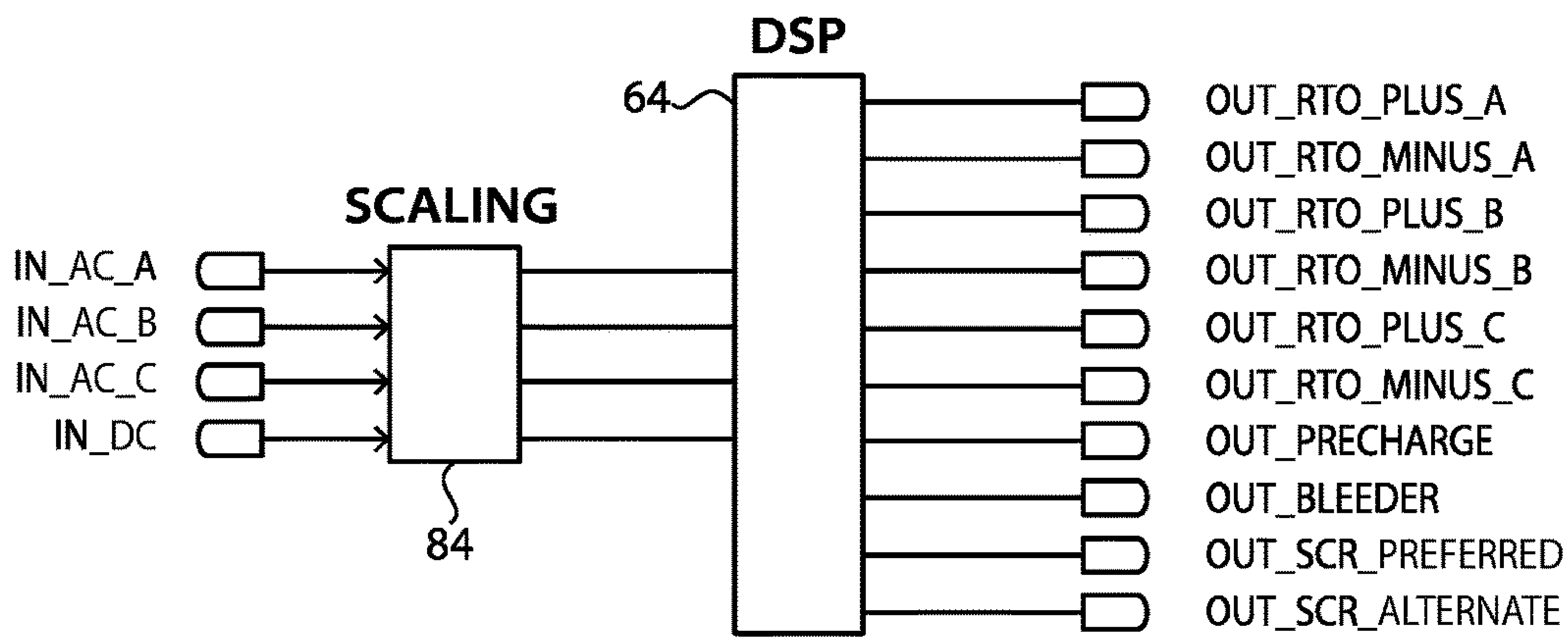

DSP
64
SCALING
IN_AC_A
IN_AC_B
IN_AC_C
IN_DC
84
OUT_RTO_PLUS_A
OUT_RTO_MINUS_A
OUT_RTO_PLUS_B
OUT_RTO_MINUS_B
OUT_RTO_PLUS_C
OUT_RTO_MINUS_C
OUT_PRECHARGE
OUT_BLEEDER
OUT_SCR_PREFERRED
OUT_SCR_ALTERNATE

FIG. 8

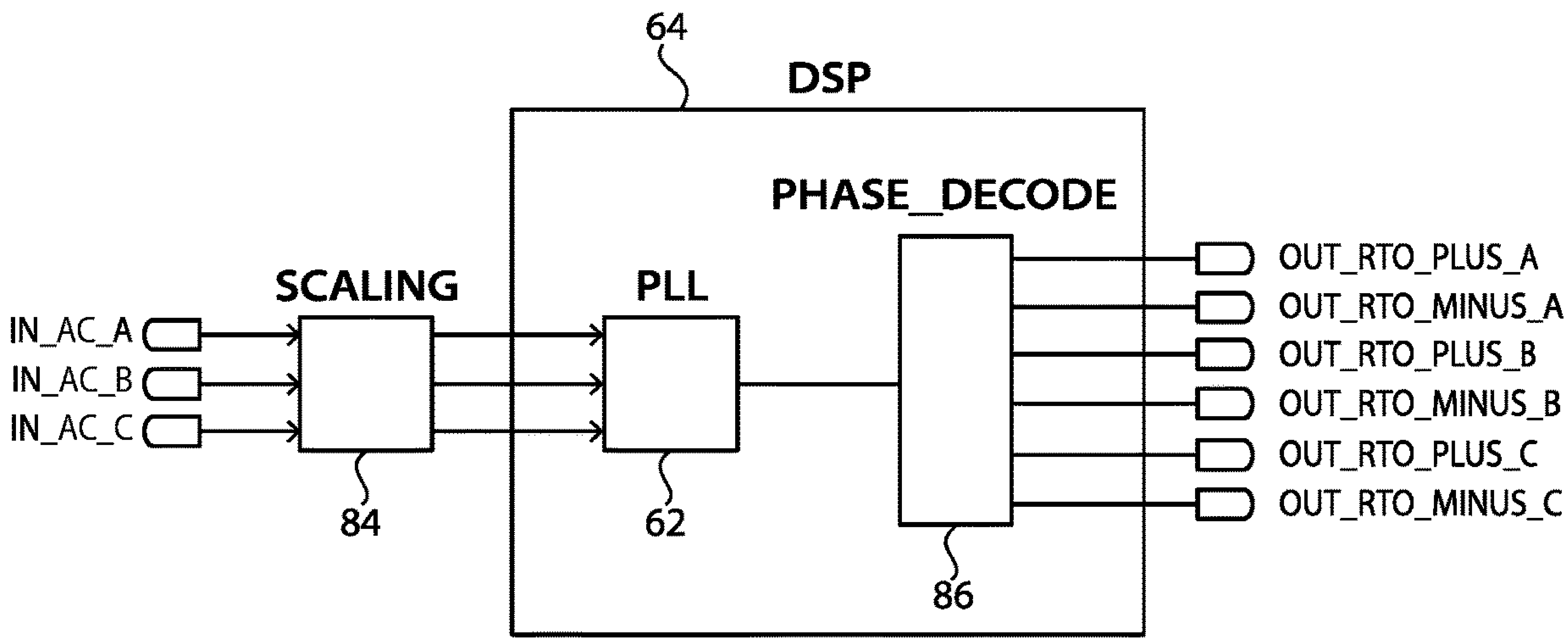

64
DSP
PHASE_DECODE
SCALING
PLL
IN_AC_A
IN_AC_B
IN_AC_C
84
62
86
OUT_RTO_PLUS_A
OUT_RTO_MINUS_A
OUT_RTO_PLUS_B
OUT_RTO_MINUS_B
OUT_RTO_PLUS_C
OUT_RTO_MINUS_C

FIG. 9

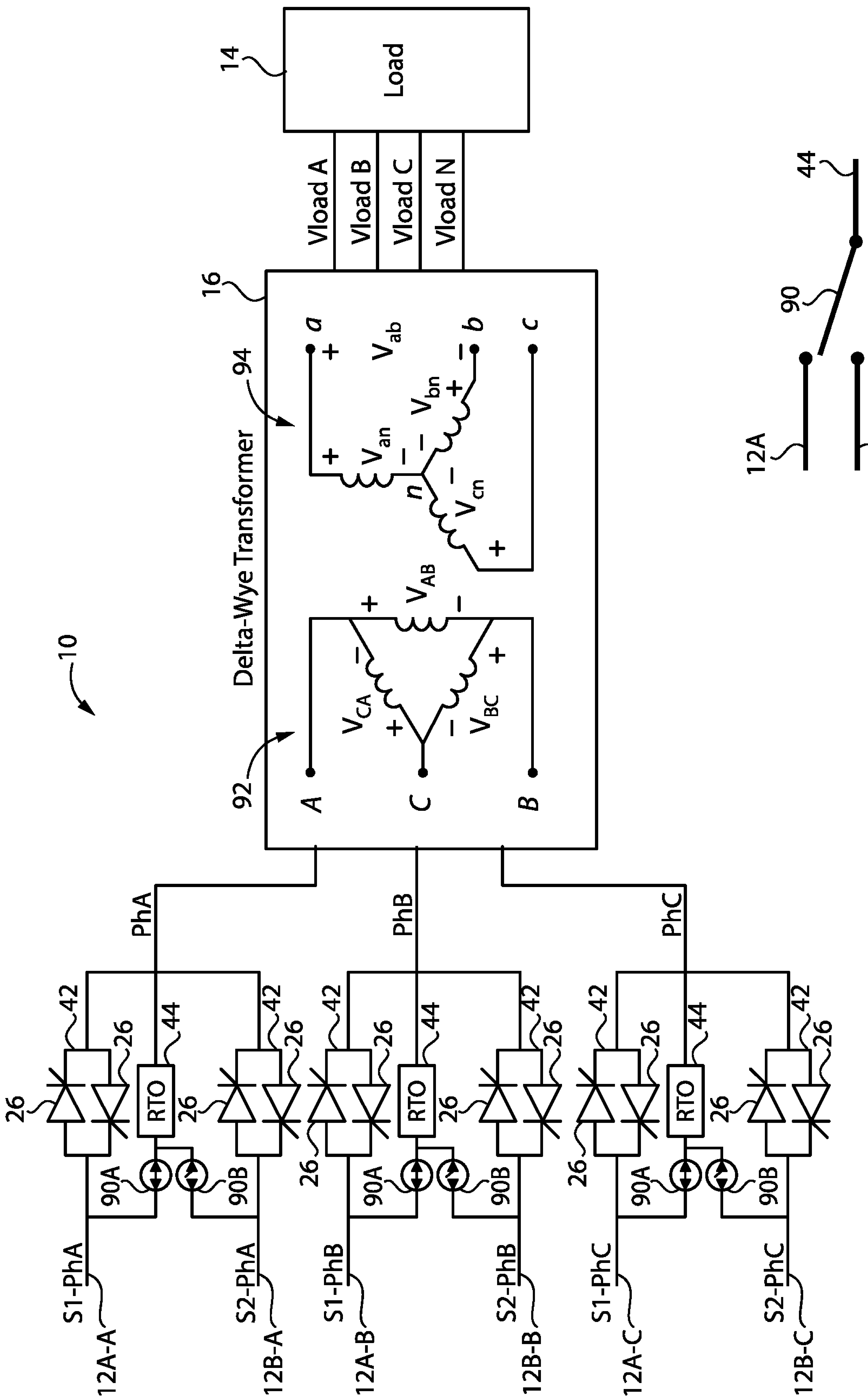


FIG. 10

FIG. 10A

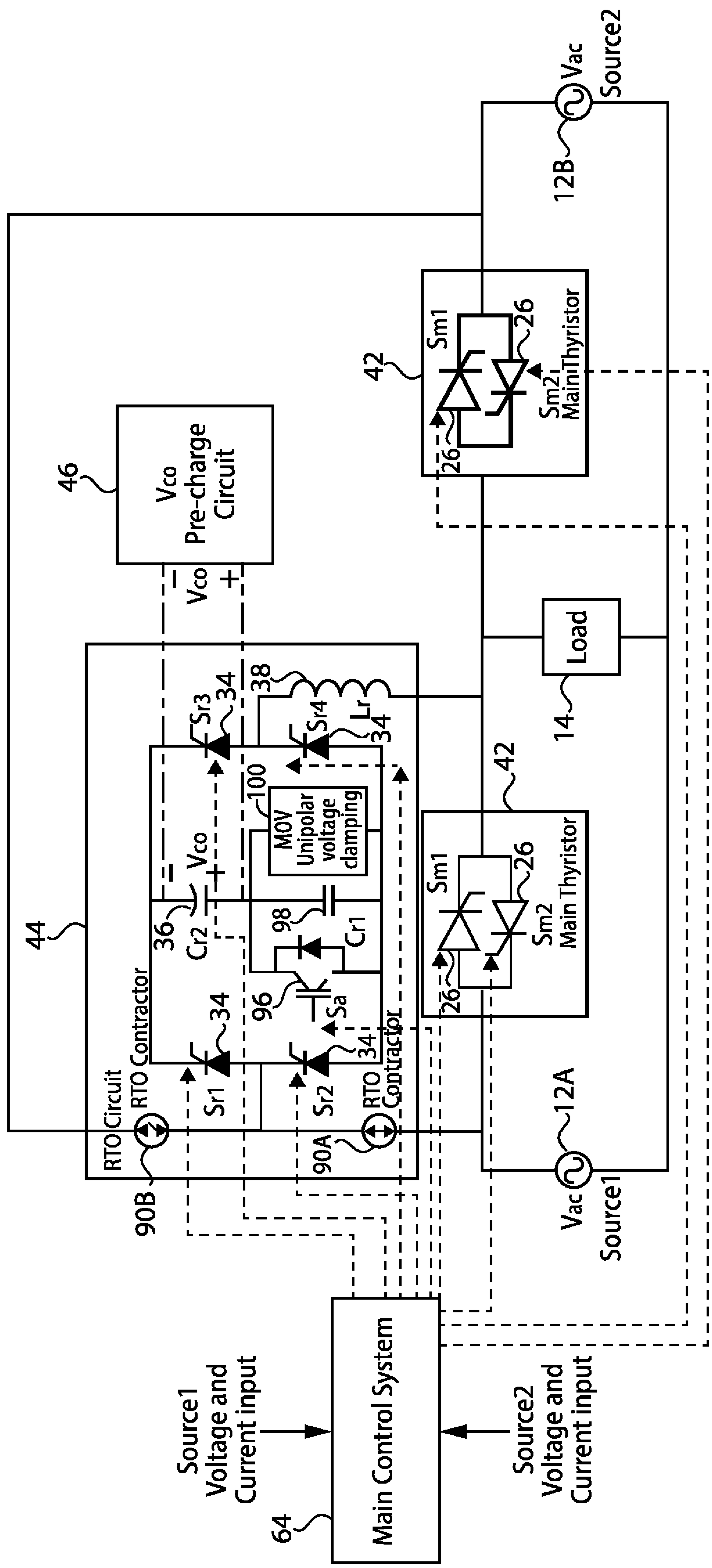

Vac
Source2
12B
42
Sm1
26
Sm2
Main Thyristor
26
46
Vco
Pre-charge
Circuit
−
Vco
+
Load
14
38
Lr
Sr3
34
Sr4
34
100
MOV
Unipolar
voltage
clamping
Vco
Cr2
36
98
Cr1
44
96
Sa
34
Sr1
Sr2
34
RTO Contractor
RTO Circuit
RTO Contractor
90B
90A
42
Sm1
26
Sm2
Main Thyristor
26
12A
Vac
Source1
Main Control System
64
Source1
Voltage and
Current input
Source2
Voltage and
Current input

FIG. 11

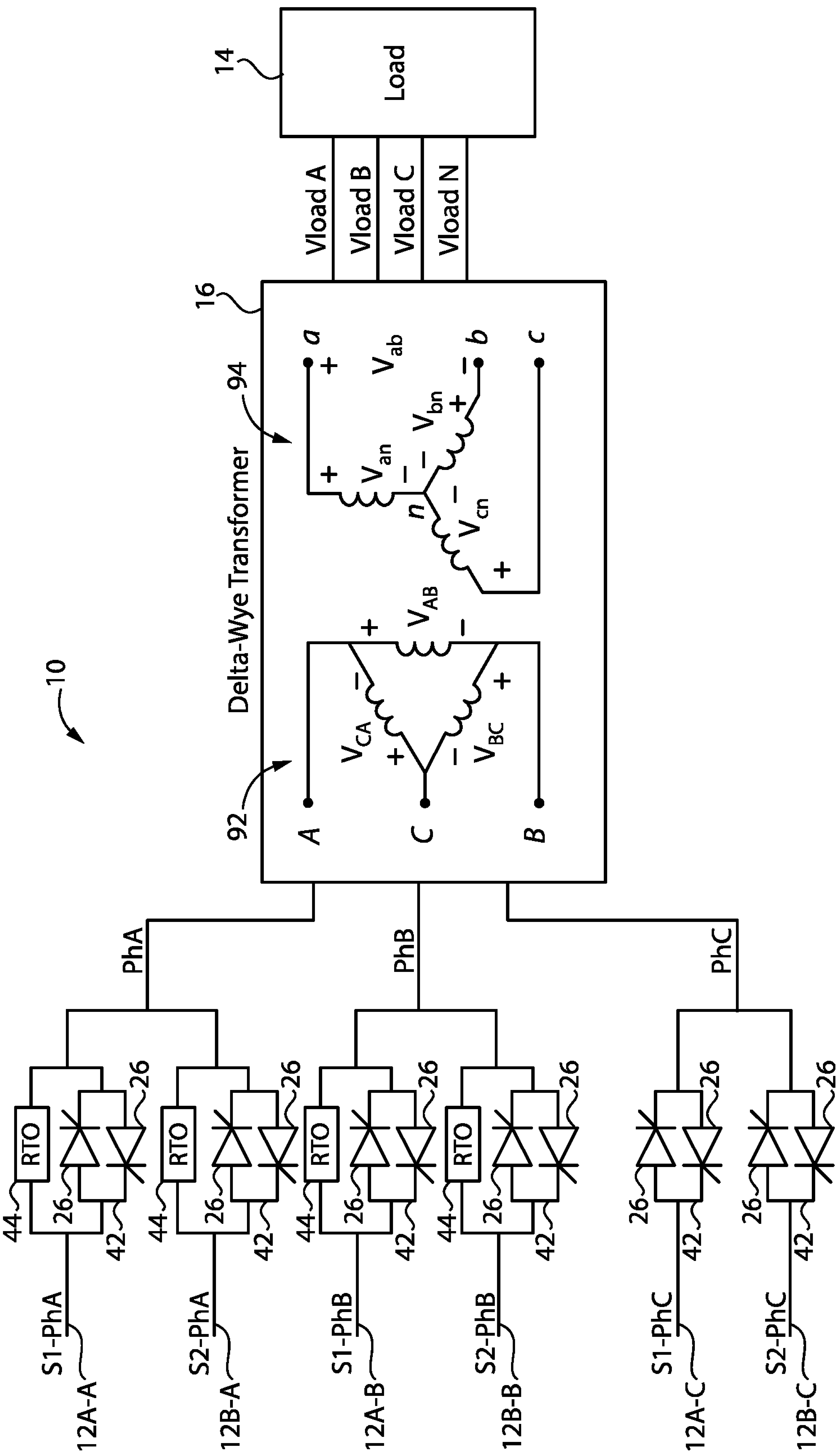

10
14
Load
Vload A
Vload B
Vload C
Vload N
16
Delta-Wye Transformer
92
94
A
B
C
a
b
c
n
V_{AB}
V_{BC}
V_{CA}
V_{ab}
V_{an}
V_{bn}
V_{cn}
PhA
PhB
PhC
RTO
26
42
44
S1-PhA
S2-PhA
S1-PhB
S2-PhB
S1-PhC
S2-PhC
12A-A
12B-A
12A-B
12B-B
12A-C
12B-C

FIG. 12

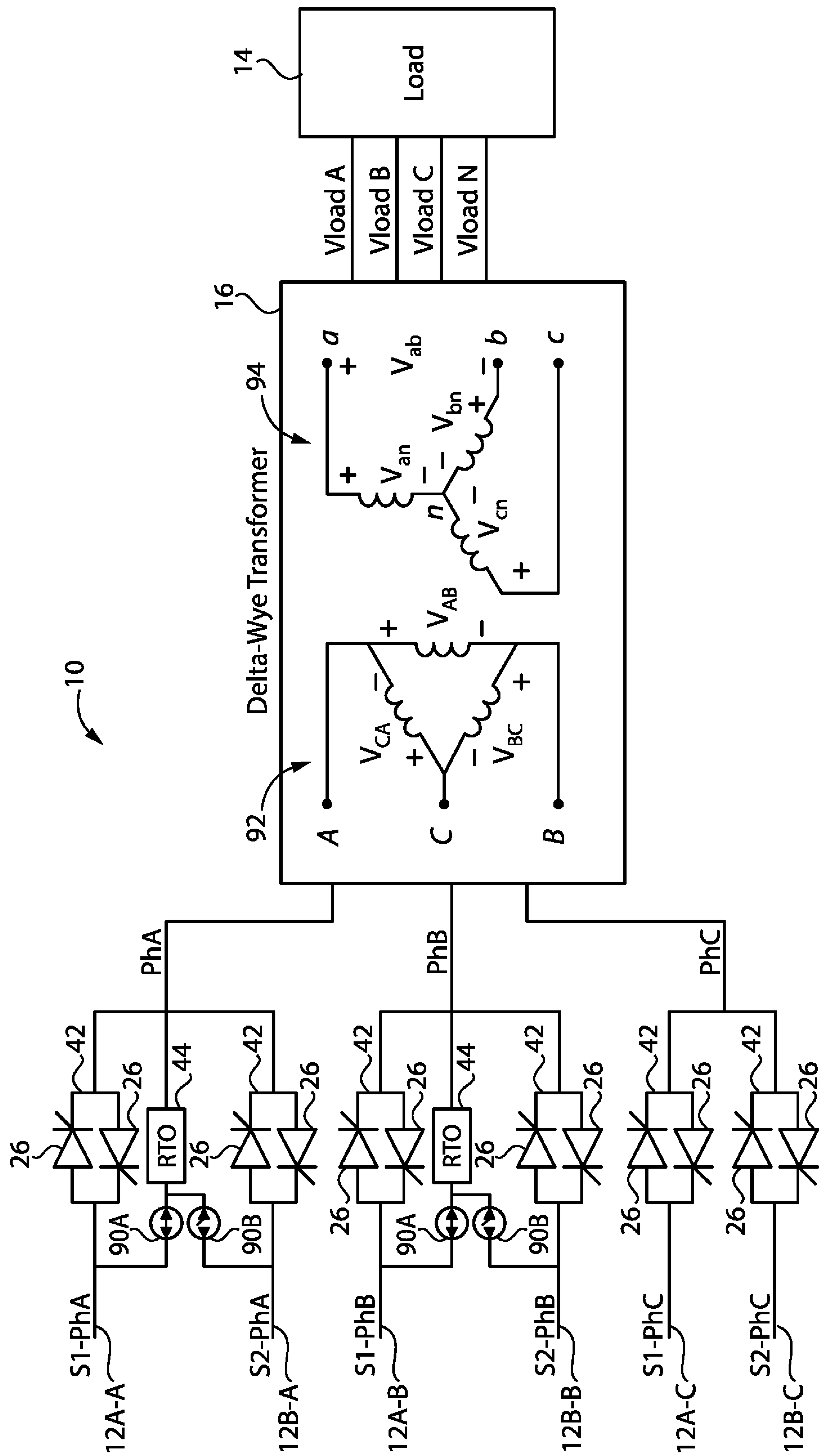

Load
14
Vload A
Vload B
Vload C
Vload N
16
Delta-Wye Transformer
94
92
10
PhA
PhB
PhC
RTO
42
44
26
90A
90B
S1-PhA
S2-PhA
S1-PhB
S2-PhB
S1-PhC
S2-PhC
12A-A
12B-A
12A-B
12B-B
12A-C
12B-C

FIG. 13

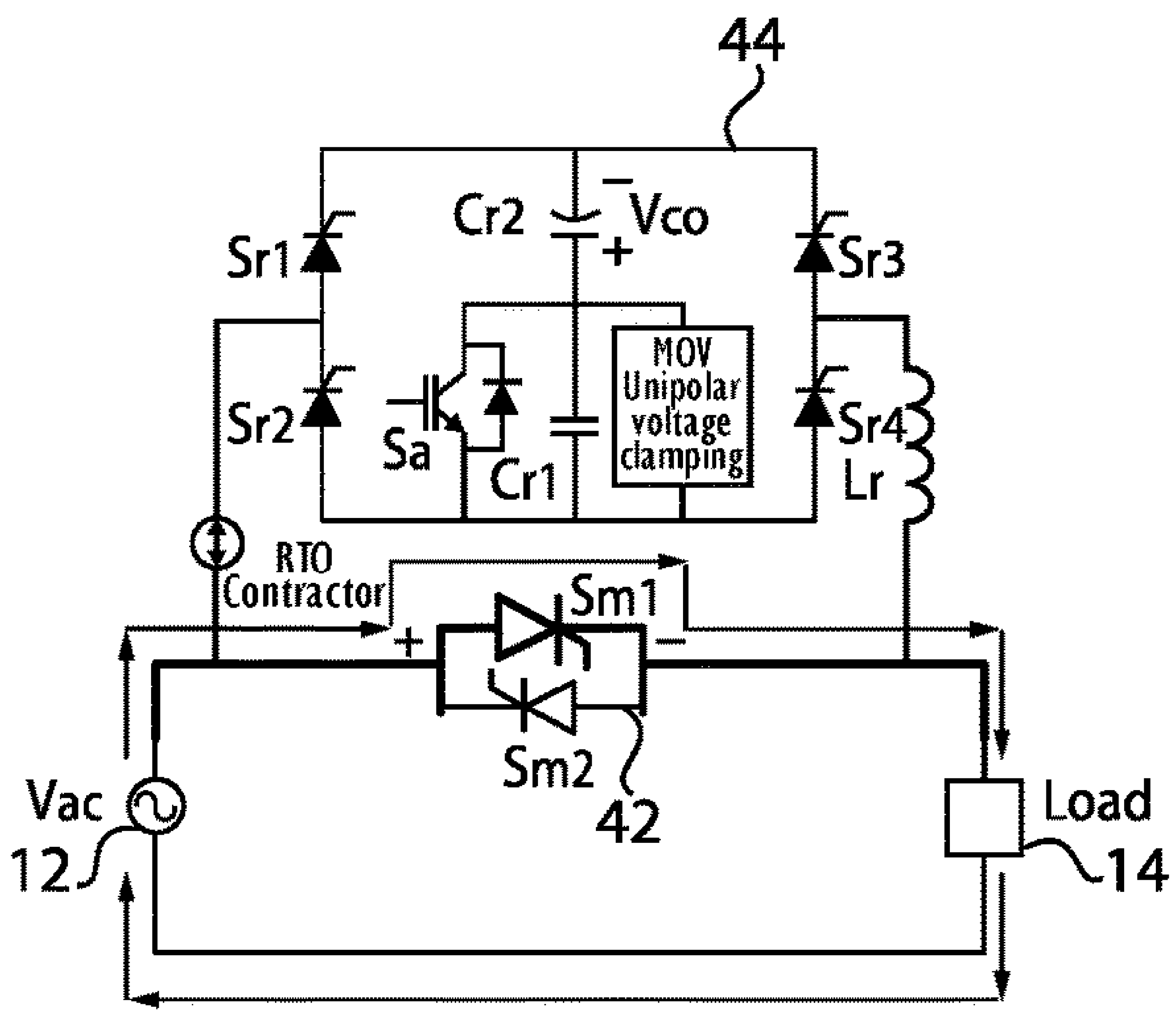


FIG. 14A

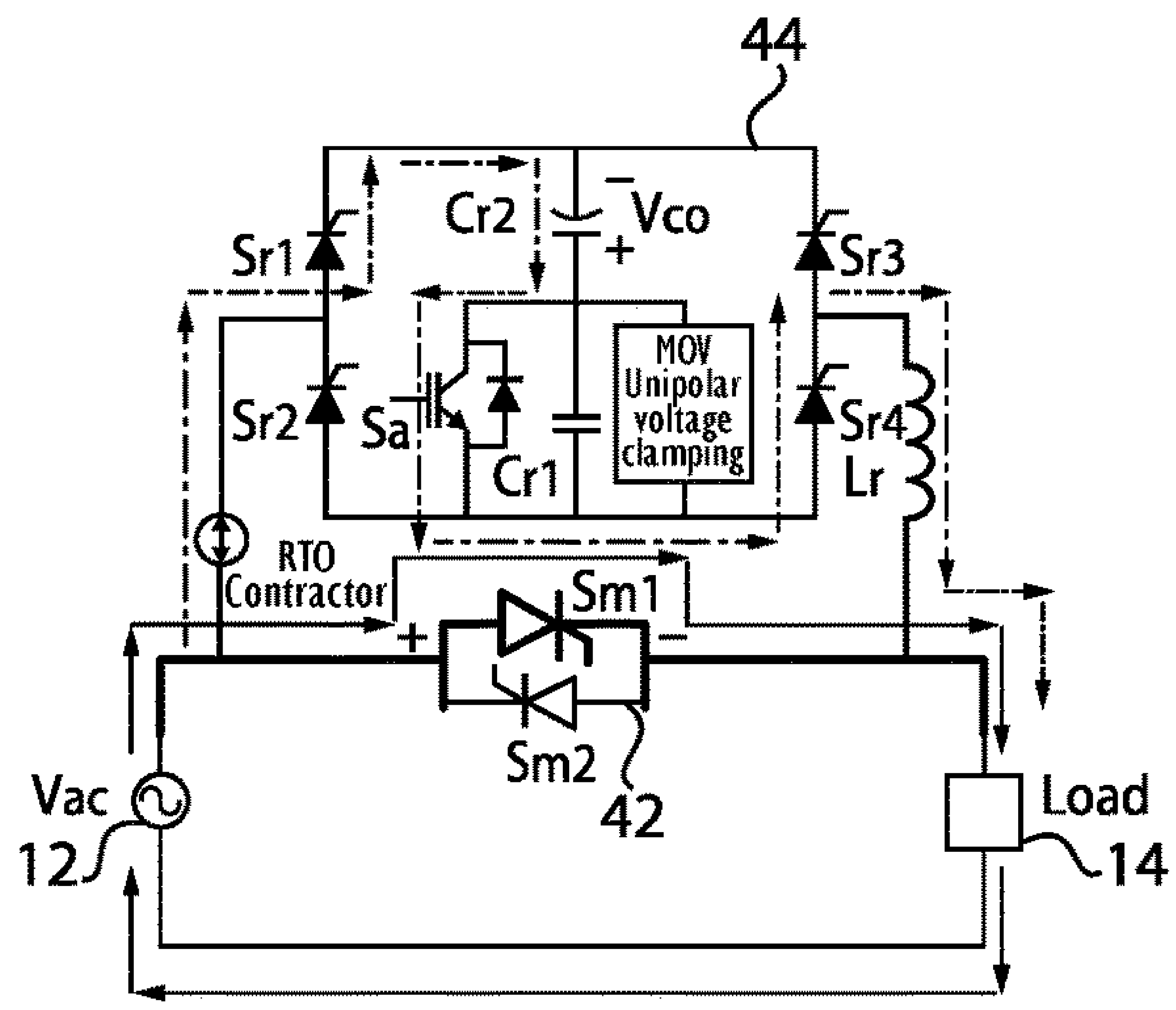


FIG. 14B

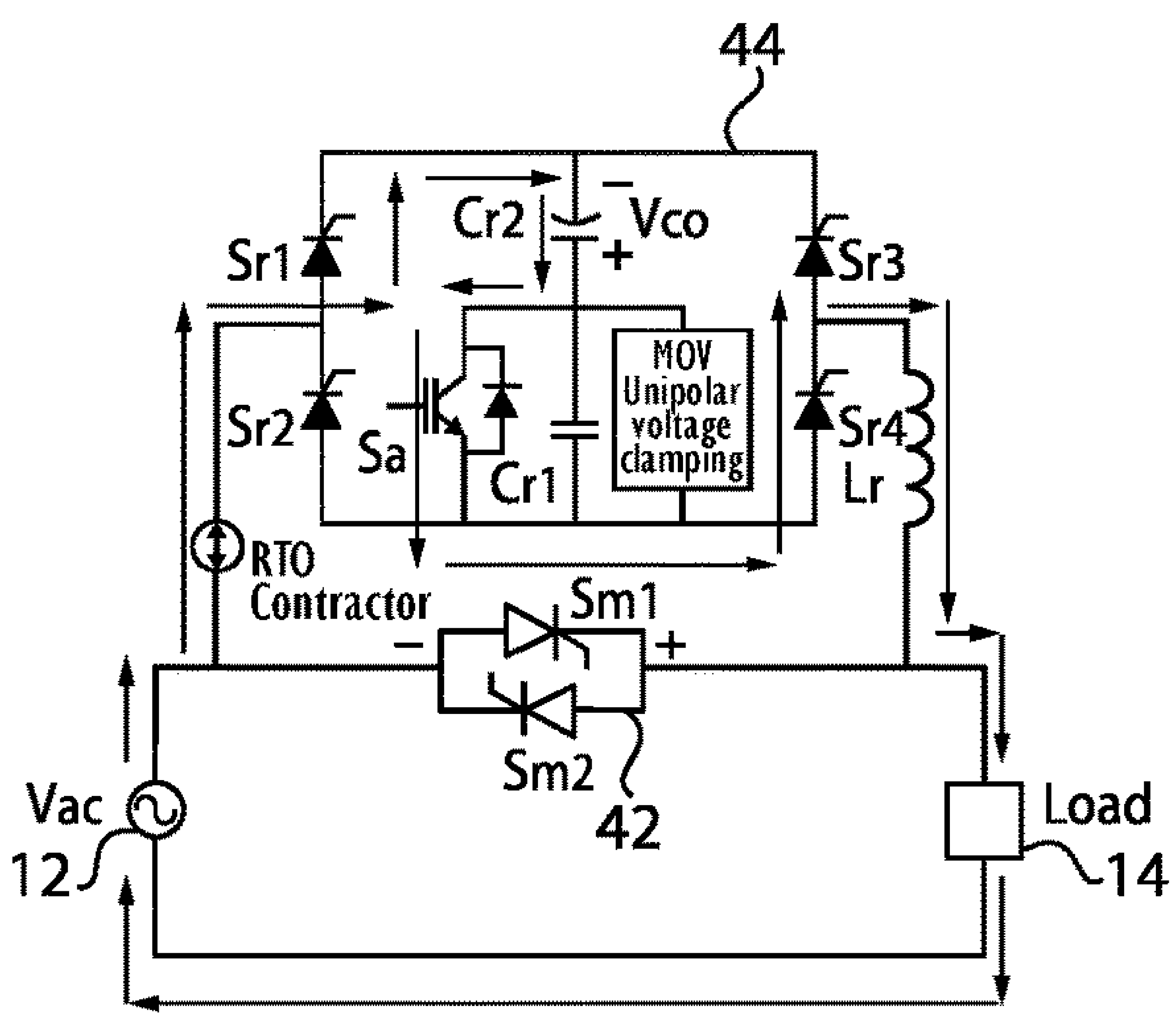


FIG. 14C

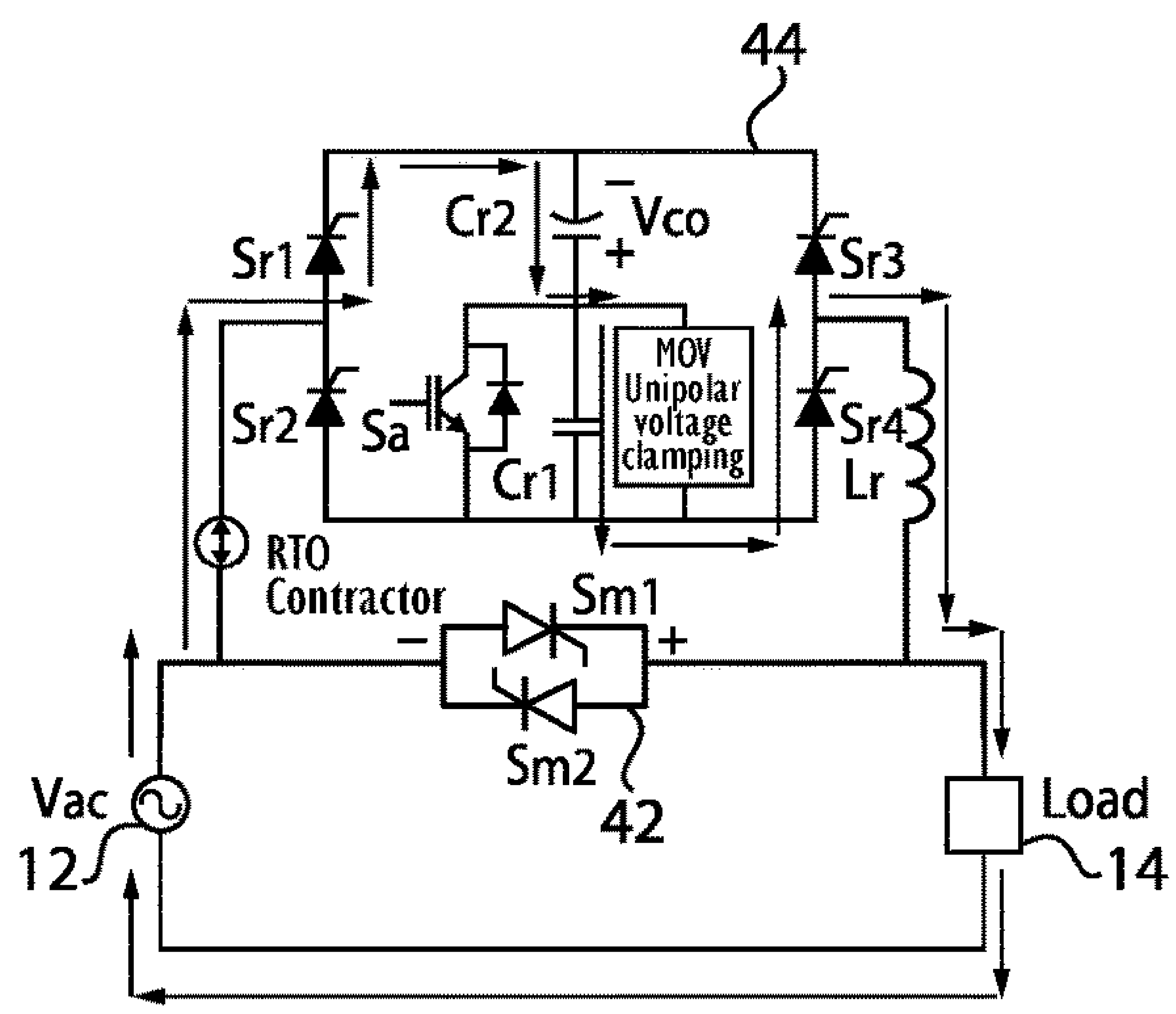


FIG. 14D

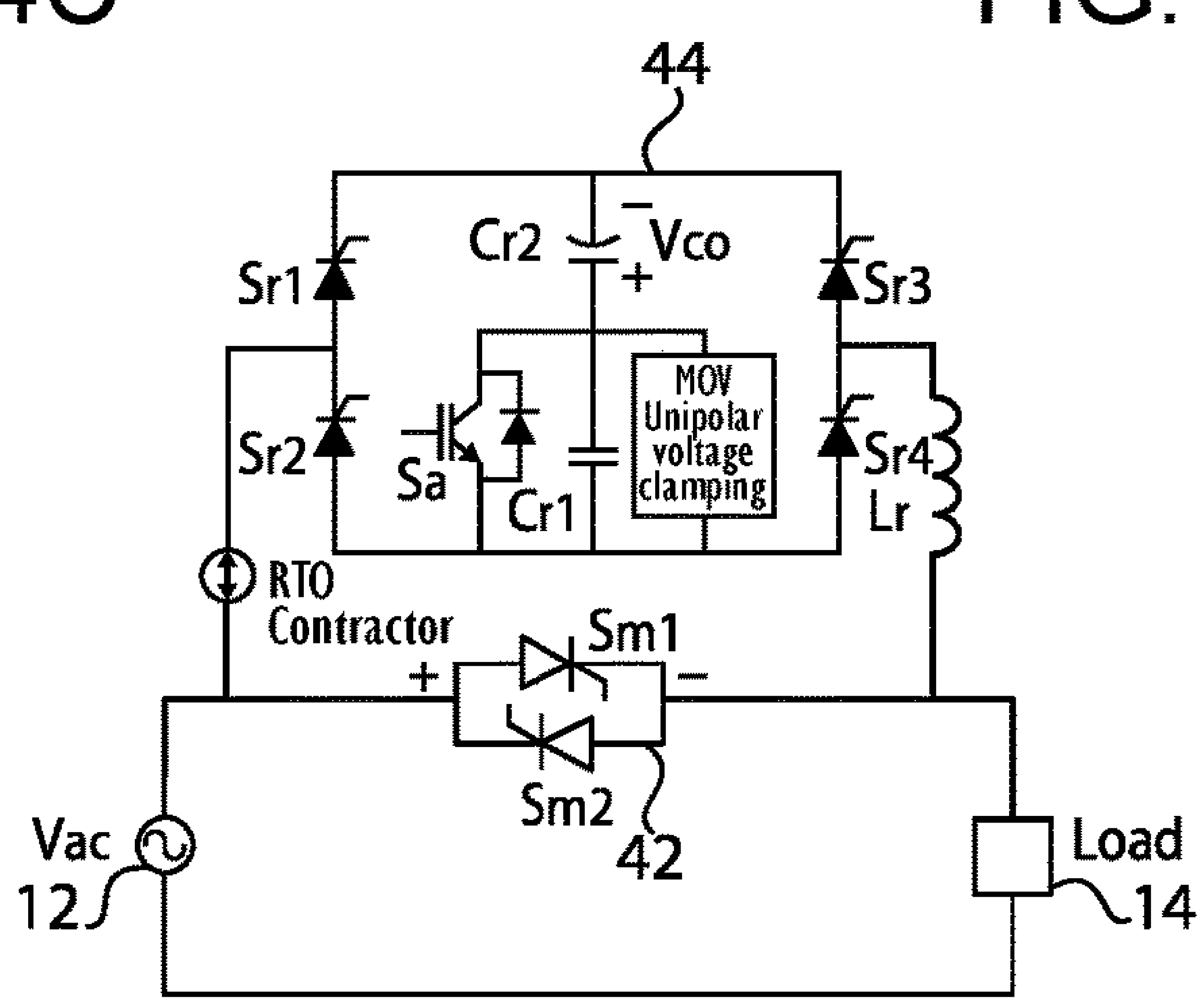
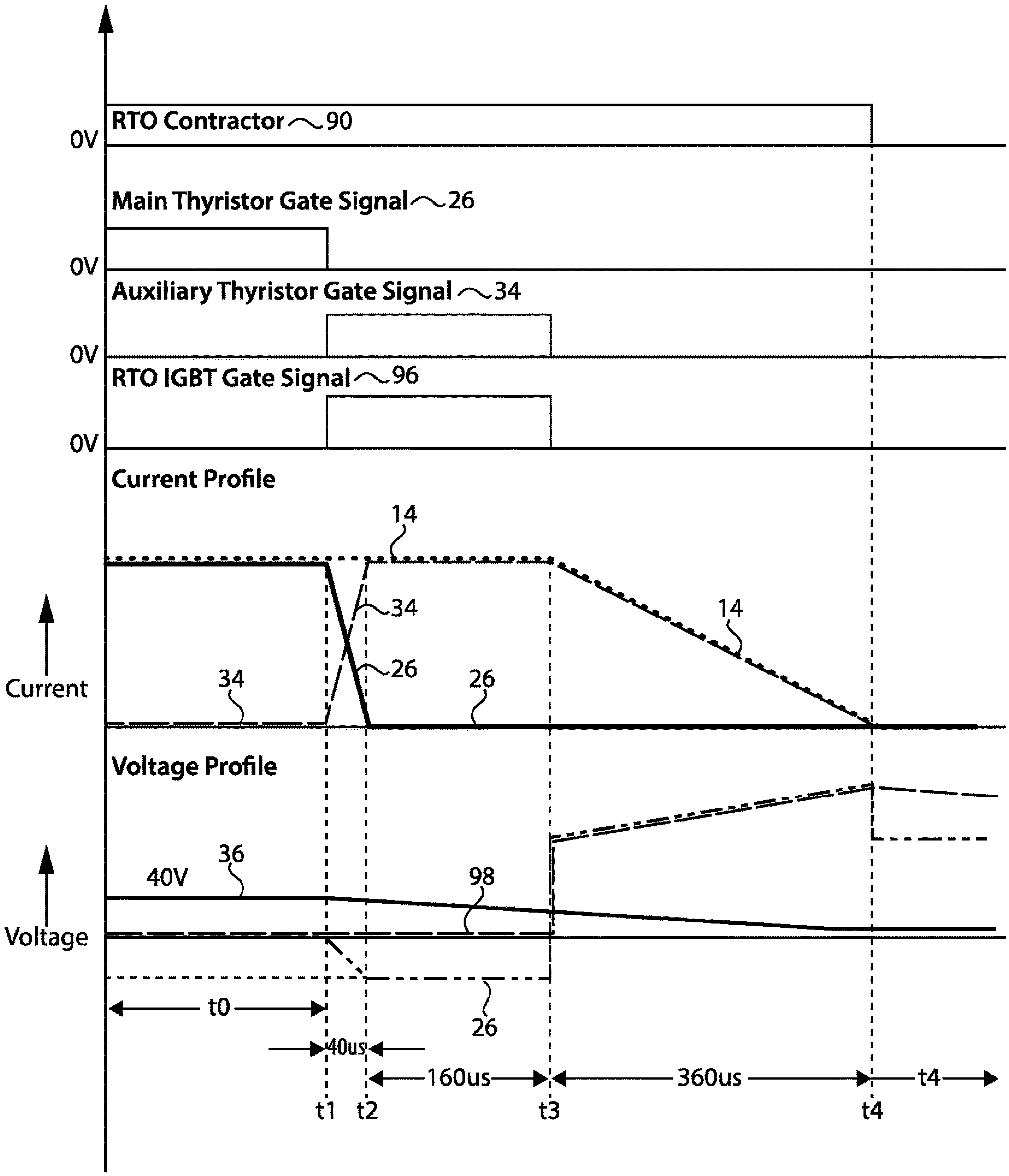


FIG. 14E



RTO Contractor 90
0V
Main Thyristor Gate Signal 26
0V
Auxiliary Thyristor Gate Signal 34
0V
RTO IGBT Gate Signal 96
0V
Current Profile
14
34
26
14
Current
34
26
Voltage Profile
Voltage
40V
36
98
26
t0
40us
160us
360us
t4
t1
t2
t3
t4

FIG. 15

DELTA CONNECTED RESONANT TURN OFF CIRCUITS

BACKGROUND

The present inventions relate generally to a static transfer switch for transferring power from one power source to another power source to supply an electrical load.

Static transfer switches are used in the industry to control the electrical power supply to critical electrical components. In particular, static transfer switches are used for electrical loads like data centers where a constant, high-quality electrical supply is required.

An example of a static transfer switch **10** is shown in FIG. **1**. As shown, two different electrical power sources **12**A, **12**B are coupled to the static transfer switch **10**. The output of the static transfer switch **10** is coupled to an electrical load **14**. Typically, the output is directly connected to a Power Distribution Unit (PDU) **14**, which includes a transformer **16**. The final electrical load may be racks of computer servers **30** (FIG. **2**) in a data center. However, it is understood that static transfer switches **10** may also be used to supply power to other types of electrical loads.

The static transfer switch **10** may include a variety of sensors **18**A, **18**B, **20**A, **20**B to monitor electrical properties of the first and second power sources **12**A, **12**B and the power output. For example, it may be desirable to monitor the voltage **18**A, **18**B of each of the power sources **12**A, **12**B and to monitor current **20**A and voltage **20**B of the output. The static transfer switch **10** also includes one or more switches **22**A, **22**B associated with each of the power sources **12**A, **12**B. This allows the static transfer switch **10** to supply power to the output from either of the power sources **12**A, **12**B. For example, the first power source **12**A may be the preferred power source **12**A (e.g., the grid), and the second power source **12**B may be a backup power source **12**B (e.g., a generator). In normal use, power can be supplied from the first power source **12**A to the load **14** by closing the first switch **22**A and opening the second switch **22**B (to disconnect the second power source **12**B). In the event that the first power source **12**A suffers from degraded performance (e.g., drop in voltage) as determined from one or more of the sensors **18**A, **18**B, **20**A, **20**B, the power supply can be transferred to the second power source **12**B by opening the first switch **22**A and closing the second switch **22**B. Thus, the electrical load **14** is provided with a constant source of power despite the possibility of degraded performance events in one of the power sources **12**A, **12**B.

SUMMARY

A static transfer switch is described for increasing the speed of switching from one power source to another power source. The system senses degraded performance of the power source supplying power to the load. In response to sensing degraded performance, the system turns off a gate signal to a first switch of each of three phases coupled between the power source and the load. The system also includes resonant turn off circuits directly connected to two of the phases which force the first switch of each respective phase to open during a switching event. One or more of the resonant turn off circuits also force the first switch of a third phase to open during the switching event through the delta side of a transformer connected to the three phases. The invention may also include any other aspect described below in the written description or in the attached drawings and any combinations thereof.

BRIEF DESCRIPTION OF SEVERAL VIEWS OF THE DRAWINGS

The invention may be more fully understood by reading the following description in conjunction with the drawings, in which:

FIG. **1** is a schematic of a static transfer switch;

FIG. **2** is a schematic of the static transfer switch showing three-phase power sources and a three-phase load;

FIG. **3** is a schematic of a switch circuit coupled between one phase of the power source and the load;

FIG. **4** is a series of graphs showing electrical properties of the switch circuit during opening of the switch between the power source and the load;

FIG. **5** is a schematic of a charge circuit for the energy storages;

FIG. **6** is another schematic of the static transfer switch;

FIG. **7** is a flow chart showing a transfer of power from one power source to another power source to supply a load;

FIG. **8** is a schematic of a digital signal processor used for controlling power through the static transfer switch;

FIG. **9** is another schematic of a digital signal processor used for controlling power through the static transfer switch;

FIG. **10** is another schematic of a static transfer switch;

FIG. **10**A is a schematic of a double throw switch;

FIG. **11** is a schematic of a resonant turn off circuit shared between two main circuits;

FIG. **12** is another schematic of a static transfer switch;

FIG. **13** is another schematic of a static transfer switch;

FIGS. **14**A-E are schematics of the operation of a resonant turn off circuit; and

FIG. **15** is a series of graphs showing electrical properties of the switch circuit of FIGS. **14**A-E.

DETAILED DESCRIPTION

An example of a three-phase static transfer switch **10** is shown in FIG. **2**. Typically, static transfer switches **10** are designed to complete a switching event between the two power sources **12**A, **12**B within one electrical cycle of the power sources **12**A, **12**B. This is desirable so that a high-quality, constant power supply is provided with minimal effect on the electrical load **14**, **30**. In order to achieve switching events this quickly, it is typically necessary to use solid-state switches **22**A, **22**B (first switches **22**A and second switches **22**B) to perform the switching event since solid-state switches **22**A, **22**B can be switched on and off in less than one electrical cycle. Preferably, the switches **22**A, **22**B are silicon controlled rectifiers (SCR). Various types of thyristors may be used for the solid-state switches **22**A, **22**B, such as integrated gate-commutated thyristors (IGCT), reverse blocking integrated gate-commutated thyristors (RB-IGCT), or gate turn-off thyristors (GTO). In the case of a multiphase static transfer switch **10**, each of the main switches **22**A, **22**B will be made up of multiple individual switches **26**, with at least one switch **26** for each phase A, B, C. A pair of anti-parallel thyristors **26** is particularly well-suited for each switch **26** associated with a phase A, B, C. Because the power sources **12**A, **12**B are AC power sources, each switch **26** typically includes two switches **26**A, **26**B in an anti-parallel arrangement. However, each pair of anti-parallel thyristors **26**A, **26**B are often treated as a single switch **26** because they typically turn on and off together.

The static transfer switch **10** may also include a series of manual switches **28** that are primarily used during maintenance to isolate sections of the circuit.

It is often preferred for the first and/or second power sources **12**A, **12**B to include an uninterruptible power supply (UPS) **32** to provide control over the electrical properties of the original source **12**A, **12**B and manage power drops or losses in the original source **12**A, **12**B. As noted, the output is typically coupled to the transformer **16** of a PDU **14**, and the final electrical load **30** is often racks of computer servers **30** in a data center.

An improvement of the invention herein is that it uses a resonant turn off topology adjusted to force commutate a three-phase power system and is operated by an embedded digital processor controlling the signals with software intelligence and algorithms in order to achieve autonomy and make possible a sub-millisecond transfer switch.

The turn off circuit **40** with RTO topology is shown in FIG. **3**. As shown, the circuit **40** includes a main circuit **42** and a resonant circuit **44**. The main thyristors **26**A, **26**B (first switches) are S_{m1} and S_{m2}. The resonant circuit includes four auxiliary thyristor switches **34** (third switches) S_{r1}, S_{r2}, S_{r3}, S_{r4}, resonant capacitor C (energy storage) **36**, and resonant inductor L **38**. The capacitor C **36** is pre-charged to provide resonant current to create a zero-current crossing for the main thyristors **26**. The inductor L **38** limits di/dt for main thyristors **26** during turn-off. During normal conduction, only the main thyristors S_{m1} (or S_{m2}) **26**A, **26**B are conducting and all the auxiliary switches **34** are off. Thus, the pre-charged resonant capacitor **36** is isolated from the main thyristor switches **26**. In resonant turn-off operation, the auxiliary switches **34** $S_{r1,2}$ (or $S_{r3,4}$ depending on current direction) are triggered to open by sending a gate signal thereto. As a result, the energy stored in the resonant capacitor **36** is discharged. When the resonant current through the inductor **38** L exceeds the load current, the current through the main thyristor **26** is commuted to the resonant circuit. In the meantime, the capacitor **36** voltage provides a negative bias voltage to help the main thyristor **26** turn off (i.e., open and stop conducting). When the main thyristor **26** current reaches zero, it starts turning off with reverse bias voltage from the resonant capacitor **36**. In the RTO topology, there are three possible design choices to control performance: resonant capacitance value C, pre-charged initial capacitor voltage V_{c0}, and resonant inductance value L. These parameters can be used to determine how much and how fast the main thyristor current can be turned off, as well as the size and cost of the auxiliary resonant circuit.

FIG. **4** shows the voltage and current waveforms of resonant turn-off operation for the main thyristors **26** and auxiliary switches **34**. As shown in the bottom graph, at time 0.1 seconds a gate signal is sent to turn off the main thyristor **26**, and a gate signal is sent to turn on the auxiliary thyristors **34**. This occurs as a result of degraded performance being identified by a sensor **18**, **20**. Because the second switches **22**B cannot be closed to switch power to the second power source **12**B until the first switches **22**A have been opened, it would be beneficial to be able to stop current conduction through the first switches **22**A faster than in a conventional static transfer switch. That is, once a turn on gate signal has been applied to an SCR, current will continue to be conducted through the SCR even after a turn off gate signal is applied. However, after a turn off gate signal is applied to the SCR, the SCR will stop conducting current after the current drops below a threshold. That normally occurs with an AC current when the current waveform crosses zero. However,

that may require up to half of an AC cycle for the power source waveform to cross zero (i.e., 8 ms). It would be beneficial to be able to stop the first switches **26**A quicker so that the second switches can be closed more quickly to transfer power as quick as possible from the first power source **12**A to the second power source **12**B. As shown in the top graph in FIG. **4**, current to the load **14**, **16** through the main and auxiliary thyristors **26**, **34** stops in less than 0.18 ms after applying the gate signals to the main and auxiliary thyristors **26**, **34**, and preferably within 0.5 ms. Thus, the turn off speed is greatly increased.

Referring to FIG. **4**, after the auxiliary resonant thyristors **34** are triggered, the resonance starts and the resonant current through L **38** increases fast. Once the resonant current is larger than the load **14**, **16** current, the main thyristor **26** current decreases to zero and starts turning off. In the meanwhile, the load **14**, **16** current is commutated or bypassed to the auxiliary circuit **44** (**34**, **36**, **38**). The resonant capacitor **36** is re-charged by the load **14**, **16** current but in reversed voltage polarity. After the resonant capacitor **36** voltage is high enough and the load **14**, **16** current is interrupted, the auxiliary thyristors **34** are turned off. As a result, the RTO has disconnected the first power source **12**A and the load **14**, **16** is ready to be transferred to the alternative power source **12**B.

The resonant circuits **44** (one for each phase) are shown in FIG. **5**. As shown, a pre-charge circuit **46** is coupled to the resonant circuits **44** with a DC bus **48**. Preferably, the DC bus **48** is pre-charged slowly through the single bridge rectifier diodes **50** with resistors **52** to make sure capacitive inrush is prevented. Also, in case the DC bus **48** runs above the set limit, a bleeding resistor **54** can be used to adjust that DC level to the desired value. A pre-charge relay **56** and bleed relay **58** are used to turn on and off the pre-charging and bleeding. Preferably, a fourth switch **60** is provided between the pre-charge circuit **46** and the capacitors **36** to disconnect the pre-charge circuit **46** from the capacitors. The fourth switch **60** is preferably opened to stop charging of the capacitors in response to the switching event. If desired, fourth switches **60** may be provided for each resonant circuit **44** to disconnect the respective circuit **44** from the DC bus **48**.

A phase locked loop (PLL) **62** (see FIG. **9**) is used to determine the frequency and phase angle of the AC waveform of the power source **12**A. The PLL **62** can be used in determining the firing sequence for the auxiliary switches **34** because the switches **34** need to be fired at the correct polarity. Since this is a three-phase system, the polarity of phase A, phase B and phase C will not be the same at the same time. The firing sequence is determined by the following algorithm:

IF 0<=PLL_RADIAN [PHASE_A]<=π
Turn ON OUT_RTO_PLUS_A
Turn OFF OUT_RTO_MINUS_A
ELSE
Turn ON OUT_RTO_MINUS_A
Turn OFF OUT_RTO_PLUS_A

The same algorithm is applied for the other remaining phases to complete the firing sequence in case a transfer is needed. In other words, only two of the auxiliary switches **34** are turned on to release current from the capacitor **36**, with one switch **34** being coupled to the input of the main thyristors **26** and the other switch **34** being coupled to the output of the main thyristors **26**. The two auxiliary switches **34** that are turned on depends on current flow of the AC current through the main switches **26**. Thus, when the current is positive, one pair of switches **34** will be turned on (while the other pair remains off), and when the current is negative, the other pair of switches **34** will be turned on (again, with the other pair remaining off). Preferably, all of the main switches **22**A, **26** are turned off (i.e., opened) and the auxiliary switches **34** are turned on (i.e., closed) at the same time in the static transfer switch **10**. Because some phases A, B, C will have a positive current and some phases A, B, C will have a negative current at the switching instant, the pair of auxiliary switches **34** that is closed in each phase resonant circuit **44** will vary depending on the current of the particular phase A, B, C.

The main circuits **42** are shown in FIG. **6**. The table below lists the names of the signals used in the main circuits **42** and the resonant circuits **44** of FIGS. **5-6**. As explained below, a DSP **64** (FIGS. **2** and **8-9**) may be used to generate the control signals used by the main circuits **42** and resonant circuits **44**.

Name	Function	Description
INPUT_AC_A	Input	Phase A voltage sensing for PLL
INPUT_AC_B	Input	Phase B voltage sensing for PLL
INPUT_AC_C	Input	Phase C voltage sensing for PLL
IN_DC	Input	Bus voltage for the capacitor
OUT_RTO_PLUS_A	Output	Phase A positive RTO
OUT_RTO_MINUS_A	Output	Phase A negative RTO
OUT_RTO_PLUS_B	Output	Phase B positive RTO
OUT_RTO_MINUS_B	Output	Phase B negative RTO
OUT_RTO_PLUS_C	Output	Phase C positive RTO
OUT_RTO_MINUS_C	Output	Phase C negative RTO
OUT_PRECHARGE	Output	Pre-charge relay control signal
OUT_BLEEDER	Output	Bleeder relay control signal
OUT_SCR_PREFERRED	Output	Preferred side SCR gating signal
OUT_SCR_ALTERNATE	Output	Alternate side SCR gating signal

FIG. **7** shows a flowchart of the method of transferring the power supply for the load **14** from one power source **12**A to another power source **12**B in a static transfer switch **10**. As understood, the method may be implemented by a controller **64**, which may be in the form of a DSP **64**. In steps **66-68**, the energy storage (capacitors **36**) are precharged by the charging circuit **46**. The voltage of the DC bus **48** between the charging circuit **46** and the resonant circuits **44** is monitored and controlled to maintain a desired charge on the capacitors **36**. That is, the relays **56**, **58** are opened and closed as needed to supply voltage and bleed voltage to charge the capacitors **36**. In step **70**, the quality of the power being supplied by the power source **12**A connected to the load **14** is monitored for degraded performance events. When such a situation is identified, the main switches **26** for the first power source **12**A are opened to disconnect the first power source **12**A from the load **14** in steps **72-78**. That is, in step **72** turn off gate signals are sent to the main switches **26**. The auxiliary switches **34** that must be turned on in each resonant circuit **44** are then determined in step **74** by phase locked loops **62** (see OUT_RTO_MINUS, OUT_RTO_PLUS algorithm above). The auxiliary switches **34** that have been determined in step **74** are then turned on with gate signals in step **76**.

In step **78**, the DSP **64** verifies that the preferred power source **12**A is completely disconnected by confirming that the net value of the current and voltage passing through the main switches **22**A, **26** for each phase of the preferred power source **12**A is zero or negligible enough to confirm that the resonant circuits **44** did in fact reverse the bias for each of the main circuits **42**. Finally, the DSP **64** can initiate a turn on command to the alternate power source **12**B in step **80**. Due to power quality considerations like inrush and soft start and preferred turn on conditions, it is possible to vary the method used to turn on the second power source **12**B while still making use of the improved method of turning off the main switches **26** of the first power source **12**A. After the main switches **22**B, **26** for the alternate power source **12** have been turned on, the power transfer has been completed in step **82**.

FIGS. **8-9** show a control system that may be used to control the resonant circuits **44**, and associated charging circuit **46**. It is understood that the control system may also be used to control the main circuits **42** as well. The Digital Signal Processor (DSP) **64** may be used to control all the relays, sense the voltages for the PLL synchronization and control the main switches **26**, **42** and RTO thyristors **34**, **44**. As shown, a scaling processor **84** may be provided to adjust the inputs for use by the DSP **64**. As also shown in FIG. **9**, the DSP **64** may include a PLL element **62** and a phase decoder element **86** to evaluate the current direction of each phase and generate the gate signals for the auxiliary switches **34**.

Static transfer switches **10** are designed to transfer power to a load **14** between a preferred electrical power source **12**A and alternate electrical power source **12**B in response to power source quality disturbances. Traditionally, thyristors **26** are commonly used in conventional static transfer switches **10** due to their high current handling capability. As a semi-controlled device, thyristors **26** cannot be turned off by simply removing the gate signal to the thyristor **26**, because a thyristor **26** is turned off when the conduction current through the thyristor **26** commutates below its minimum holding current (usually less than 1 A) or the voltage applied to the thyristor **26** is reversed, which can be as long as half a cycle of the power source **12** fundamental frequency (e.g., 8.3 ms in 60 Hz AC systems). To speed up commutation of the thyristors **26**, a resonant turn off (RTO) circuit **44** may be used as described above and below, where the resonant turn off circuit **44** is added in parallel to the thyristors **26**. During thyristor **26** turn-off, a reverse current is injected by the resonant turn off circuit **44** to force the thyristor **26** current to commutate quickly to zero. In this way, the resonant turn off circuit **44** can interrupt the current within 1 ms, or preferably less than a half cycle of the power sources **12**, which greatly shortens the disconnect time of the off going electrical power source **12**. Typically, each phase A, B, C of each power source **12** has an individual resonant turn off circuit **44** in order to quickly turn off each phase during a transfer and to allow quick transfers back-and-forth in both directions between the power sources **12**. Thus, six resonant turn off circuits **44** are required in for a two source static transfer switch **10**. Likewise, nine resonant turn off circuits **44** would be needed in a three source static transfer switch **10**.

As shown in FIGS. **10-11**, the number of resonant turn off circuits **44** may be reduced by sharing the resonant turn off circuit **44** between the phases A, B, C of different power sources **12**A, **12**B. This may be useful in reducing the cost and complexity of the static transfer switch **10**. As shown, an AC contactor or relay **90** may be used to select which power source **12**A, **12**B the resonant turn off circuit **44** is connected to. Various types of switches **90** (i.e., a fourth and fifth switch) may be used to connect the resonant turn off circuit **44** to a selected power source **12**A, **12**B, although an electro-mechanical switch **90** may be preferred due to the low cost, high capacity and reliability of such switches. Since the switching times of the contactors **90** is not critical because the contactors **90** are not directly involved in the actual switching event of turning off the thyristors **26**A of one source **12**A and turning on the thyristors **26**B of the other source **12**B, contactors **20** with slower switching times than the main thyristors **26**A and/or the auxiliary thyristors **34** may be used. Although individual contactors **90**A, **90**B may be used, with each contactor **90**A, **90**B corresponding to one of the power sources **12**A, **12**B and one of the phases A, B, C, a single double throw switch **90** as shown in FIG. **10**A may incorporate two switches **90**A, **90**B (i.e., the fourth and fifth switch) into one physical switch **90**. In use, the contactors **90**A, **90**B connect the shared resonant turn off circuit **44** to the main circuit **42** of the power source **12**A, **12**B that is currently supplying power to the electrical load **14**. As a result, the resonant turn off circuit **44** is connected to and prepared to quickly turn off current through the operating main circuit **42** when a power transfer switching event is initiated. For example, when the thyristors **26** of the first power source **12**A are closed such that power is being supplied from the first power source **12**A to the load **14**, the first contactors **90**A are closed to connect the shared resonant turn off circuits **44** to the first thyristors **26** and the second contactors **90**B are open to disconnect the shared resonant turn off circuits **44** from the second thyristors **26**. Conversely, when the thyristors **26** of the second power source **12**B are closed such that power is being supplied from the second power source **12**B to the load **14**, the second contactors **90**B are closed to connect the shared resonant turn off circuits **44** to the second thyristors **26** and the first contactors **90**A are open to disconnect the shared resonant turn off circuits **44** from the second thyristors **26**. As a result of the shared arrangement of the resonant turn off circuits **44**, the number of resonant turn off circuits **44** can be reduced to three instead of six as required in a conventional two source static transfer switch **10**. Similarly, in a three source system, the number of resonant turn off circuits **44** could be reduced from nine to three. The contactors **90** may also be useful in protecting the resonant turn off circuits **44** and/or isolating the circuits **44** during fault conditions (e.g., thyristor **26**, **34** or IGBT **96** failures).

As shown in FIG. **12**, the number of resonant turn off circuits **44** may also be reduced by eliminating the resonant turn off circuits **44** from one phase C of a three phase system. Thus, as shown resonant turn off circuits **44** may be directly connected to the main circuits **42** of two of the phases A, B. In this arrangement, when the two main circuits **42** are turned off with the respective resonant turn off circuits **44**, current flow from the third phase C is also forced to zero automatically through the delta input side **92** of the transformer **16** between the main circuits **42** and the electrical load **14**. For example, in a power transfer switching event where power is initially being supplied by the first power source **12**A, the resonant turn off circuits **44** directly connected to the main circuits **42** for phases **12**A-A and **12**A-B (i.e., phases A & B of source **12**A) are activated. This causes the respective main circuits **42** to open and phases **12**A-A and **12**A-B to be disconnected from the load **14**. One or both of the two resonant turn off circuits **44** then force the remaining main circuit **42** for phase **12**A-C to open through the delta side **92** of the transformer **14** which disconnect the remaining main circuit **42** from the load **14**. Even though the third phase C may not have its own resonant turn off circuit **44**, the current released by the two resonant turn off circuits **44** and the current conducted by all three main circuits **42** may cease flowing to the transformer **16** within 0.5 ms of the gate signals sent to the main circuits **42** or within less than half a cycle of the power source **12**. The main circuits **42** for phases **12**B-A, **12**B-B, **12**B-C are then closed to connect the second power source **12**B to the load **14**. Preferably, the two resonant turn off circuits **44** are activated at the same time by closing the corresponding auxiliary switches **34** at the same time such that current from both resonant turn off circuits **44** forces the remaining main circuit **42** to open through the delta side **92** of the transformer **16**. Preferably, the output side of the transformer **16** is a wye side output **94**. Thus, whereas a conventional static transfer switch **10** would have a separate resonant turn off circuit **44** for each phase A, B, C of a three-phase electrical power source **12**, the present embodiment may be used to eliminate the resonant turn off circuit **44** from one of the phases C such that no resonant turn off circuit **44** is directly connected to the main circuit **42** of one phase C. As a result of the delta connected resonant turn off circuits **44**, the number of resonant turn off circuits **44** can be reduced to four instead of six as required in a conventional two source static transfer switch **10**. Similarly, in a three source system, the number of resonant turn off circuits **44** could be reduced from nine to six.

As shown in FIG. **13**, the designs of FIGS. **10** and **12** may also be combined to reduce the number of resonant turn off circuits **44** even further. Thus, the static transfer switch **10** may have shared resonant transfer circuits **44** between two corresponding phases A, B of the power sources **12**A, B and may have one phase C connected through the delta side **92** of the transformer **16** that does not have its own resonant transfer circuit **44**. As a result, the number of resonant turn off circuits **44** may be reduced from six to two in a two source system and from nine to two in a three source system.

The operation of the resonant turn off circuit **44** of FIG. **11** is illustrated in FIGS. **14**A-E (refer to FIG. **11** for detailed reference numbers), and the voltage and current is shown in FIG. **15**. It is understood, however, that any type of resonant turn off circuit **44** may be used including the resonant turn off circuit **44** of FIGS. **3** and **5**. The capacitor **36** may be pre-charged to a relatively low voltage (40~50 V) and provides a resonant current to create a zero-current crossing for main circuit **42**. A pre-charge circuit **46** may be provided for pre-charging the capacitor **36**. The resonant inductor **38** limits the change in current to provide a softer commutation. As shown in FIG. **14**A, before t**1**, the main thyristors **26** conduct current to the load **14**. In FIG. **14**B, at t**1**, when a switching event is initiated, the gate signal to at least one of the main thyristors **42** is turned off, depending on the load current direction, and the corresponding auxiliary thyristors **34** and the IGBT **96** are closed with a gate signal. For example, in FIG. **4**(*a*), Sm**1** conducts the load current. From t**1** to t**2**, in FIG. **14**B, load current is forced to commutate from the main thyristor **26** to the resonant turn off circuit **44**. In FIG. **14**C, at t**2**, reversed bias voltage from the capacitor **36** is applied to the anode of the main thyristor **26** to speed up its turn-off. As shown in FIG. **15**, the capacitor **36** discharges and voltage of the capacitor **36** drops during this period. The energy stored in the capacitor **36** is preferably large enough to maintain the voltage polarity and reverse the bias to the main thyristor **26**. The period between t**2** and t**3** allows sufficient time for the main thyristor **26** to commutate. In FIG. **14**D, at t**3**, the main thyristor **26** is completely blocks forward voltage, and the auxiliary thyristors **34** and IGBT **96** are commanded to turn-off. From t**3** to t**4**, in FIG. **14**D, the voltage of the resonant capacitor **98** increases until reaching the clamping voltage. In FIG. **14**E, loop energy has been absorbed by the snubber circuit **100**, and the load current is zero and has been completely interrupted at t**4**. It is understood that a variety of resonant turn off circuits **44** may be used herein, with additional examples being provided in U.S. patent application Ser. No. 16/795,988, which is incorporated by reference herein.

While preferred embodiments of the inventions have been described, it should be understood that the inventions are not so limited, and modifications may be made without departing from the inventions herein. While each embodiment described herein may refer only to certain features and may not specifically refer to every feature described with respect to other embodiments, it should be recognized that the features described herein are interchangeable unless described otherwise, even where no reference is made to a specific feature. It should also be understood that the advantages described above are not necessarily the only advantages of the inventions, and it is not necessarily expected that all of the described advantages will be achieved with every embodiment of the inventions. The scope of the inventions is defined by the appended claims, and all devices and methods that come within the meaning of the claims, either literally or by equivalence, are intended to be embraced therein.

The invention claimed is:

1. A static transfer switch, comprising:
- a first three-phase electrical power source comprising a first phase A, a first phase B and a first phase C;
- a second three-phase electrical power source comprising a second phase A, a second phase B and a second phase C;
- a three-phase transformer comprising a delta side with a phase A input, a phase B input and a phase C input;
- a first phase A switch between the first phase A and the phase A input to the delta side of the three-phase transformer;
- a second phase A switch between the second phase A and the phase A input to the delta side of the three-phase transformer;
- a first phase B switch between the first phase B and the phase B input to the delta side of the three-phase transformer;
- a second phase B switch between the second phase B and the phase B input to the delta side of the three-phase transformer;
- a first phase C switch between the first phase C and the phase C input to the delta side of the three-phase transformer;
- a second phase C switch between the second phase C and the phase C input to the delta side of the three-phase transformer;
- a first resonant turn off circuit coupled to the first phase A switch;
- a second resonant turn off circuit coupled to the first phase B switch;
- wherein during a switching event, the first and second resonant turn off circuits force the first phase A switch and the first phase B switch to open, respectively, through a direct connection therebetween to disconnect the first phase A and the first phase B from the three-phase transformer;
- wherein during the switching event, the first and/or second resonant turn off circuits force the first phase C switch to open through the delta side of the three-phase transformer to disconnect the first phase C from the three-phase transformer; and
- wherein the during the switching event, the second phase A switch, the second phase B switch and the second phase C switch are closed to connect the second three-phase electrical power source to the three-phase transformer.

2. The static transfer switch according to claim 1, wherein the first and second resonant turn off circuits each comprise an energy storage and a third switch, the third switches being closed during the switching event to connect the energy storages to the first phase A switch and the first phase B switch in order to force the first phase A switch and the first phase B switch to open.

3. The static transfer switch according to claim 2, wherein the third switches comprise thyristors.

4. The static transfer switch according to claim 2, wherein the first and second resonant turn off circuits each comprise two of the third switch, one of the third switches being coupled to the inputs of the first phase A switch and the first phase B switch, respectively, and another of the third switches being coupled to the outputs of the first phase A switch and the first phase B switch, respectively, each of the energy storages being disposed between the two third switches.

5. The static transfer switch according to claim 2, wherein the first and second resonant turn off circuits each comprise two of the third switch, the two third switches both being disposed between the respective energy storage and the inputs or the outputs of the first phase A switch and the first phase B switch, respectively, one of the two third switches being closed if a positive current is being conducted through the first phase A switch and the first phase B switch, respectively, and another of the two third switches is closed if a negative current is being conducted through the first phase A switch and the first phase B switch, respectively.

6. The static transfer switch according to claim 2, wherein the first and second resonant turn off circuits each comprise four of the third switches, two of the third switches being coupled to the inputs of the first phase A switch and the first phase B switch, respectively, and two of the third switches being coupled to the outputs of the first phase A switch and the first phase B switch, respectively, each of the energy storages being disposed between two of the third switches on one side and two of the third switches on another side, wherein two of the third switches on opposite sides of each of the energy storages are closed if a positive current is being conducted through the first phase A switch and the first phase B switch, respectively, and a different two of the third switches on opposite sides of each of the energy storages are closed if a negative current is being conducted through the first phase A switch and the first phase B switch, respectively.

7. The static transfer switch according to claim 2, further comprising an inductor coupled between the inputs or outputs of the first phase A switch and the first phase B switch, respectively, and the respective third switch.

8. The static transfer switch according to claim 2, wherein each of the energy storages is a capacitor.

9. The static transfer switch according to claim 2, further comprising a charge circuit to maintain a predetermined charge of the energy storages.

10. The static transfer switch according to claim 2, wherein each of the third switches is closed at the same time.

11. The static transfer switch according to claim 1, wherein the three-phase transformer comprises a wye side output.

12. The static transfer switch according to claim 1, wherein the first phase C switch has no resonant turn off circuit directly connected thereto.

13. The static transfer switch according to claim 1, wherein the second phase A switch and the second phase B switch have resonant turn off circuits directly connected thereto and the second phase C switch has no resonant turn off circuit directly connected thereto.

14. The static transfer switch according to claim 1, wherein a current released by the first and second resonant turn off circuits, respectively, and a current conducted through the first phase A switch, the first phase B switch and the first phase C switch, respectively, ceases to flow to the three-phase transformer within 0.5 ms of turning off a gate signal to the first phase A switch and the first phase B switch, respectively, during respective switching events.

15. The static transfer switch according to claim 1, wherein the first and second resonant turn off circuits force the first phase A switch, the first phase B switch and the first phase C switch to open in less than one half an electrical cycle of the first three-phase electrical power source.

16. The static transfer switch according to claim 1, wherein the first phase A switch, first phase B switch and the first phase C switch comprise silicon controlled rectifiers.

17. The static transfer switch according to claim 1, wherein the first phase A switch, first phase B switch and the first phase C switch comprise integrated gate-commutated thyristors (IGCT), reverse blocking integrated gate-commutated thyristors (IGCT), or gate turn-off thyristors (GTO).

18. The static transfer switch according to claim 1, wherein the three-phase transformer supplies electrical power to a data center.

19. The static transfer switch according to claim 1, wherein one of the first and second three-phase electrical power sources comprises an uninterruptible power supply (UPS).

20. The static transfer switch according to claim 1, further comprising:

a fourth switch between the first resonant turn off circuit and the first phase A switch;

another fourth switch between the second resonant turn off circuit and the first phase B switch;

a fifth switch between the first resonant turn off circuit and the second phase A switch;

another fifth switch between the second resonant turn off circuit and the second phase B switch;

wherein the fourth switches are closed to connect the first and second resonant turn off circuits to the first phase A and B switches when the first phase A and B switches are closed and connecting the first electrical power source to the electrical load; and

wherein the fifth switches are closed to connect the first and second resonant turn off circuits to the second phase A and B switches when the second phase A and B switches are closed and connecting the second electrical power source to the electrical load.

21. A static transfer switch, comprising:

a set of first power inputs coupled to a first three-phase electrical power source, each of the first power inputs being coupled to one phase of the first three-phase electrical power source;

a set of second power inputs coupled to a second three-phase electrical power source, each of the second power inputs being coupled to one phase of the second three-phase electrical power source;

a set of power outputs coupled to a delta side of a three-phase transformer;

a set of first switches coupled between the set of first power inputs and the set of power outputs;

a set of second switches coupled between the set of second power inputs and the set of power outputs;

a set of third switches coupled between a set of energy storages and two of the first switches, each third switch being coupled between one of the energy storages and a respective first switch;

a sensor to determine an electrical property of the first three-phase electrical power source;

a power transfer controller, the sensor being an input to the power transfer controller and the sets of first and second switches being outputs of the power transfer controller;

wherein during normal operation the power transfer controller closes the set of first switches to electrically connect the set of first power inputs and the set of power outputs together and opens the set of second switches to electrically disconnect the set of second power inputs and the set of power outputs, the first three-phase electrical power source thereby supplying power to the three-phase transformer;

wherein when the sensor identifies degraded performance of the first three-phase electrical power source, the power transfer controller initiates a switching event, comprising:

turning off a gate signal to each of the first switches;

closing at least one third switch between each of the two first switches and each respective energy storage after the gate signal of the respective first switch has been turned off, the set of energy storages thereby releasing a current to the input or output of the respective first switch to force a drop in current conducted through the respective first switch, the drop in current causing the respective first switch to open and stop conducting current therethrough between the first three-phase electrical power source and the three-phase transformer;

opening a third one of the first switches with current conducted from one or more of the energy storages through the delta side of the three-phase transformer to force a drop in current conducted through the third one of the first switches, the drop in current causing the third one of the first switches to open and stop conducting current therethrough between the first three-phase electrical power source and the three-phase transformer without a separate energy storage or third switch for the third one of the first switches;

closing the set of second switches after respective first switches have been opened, the second three-phase electrical power source thereby supplying power to the three-phase transformer.

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